# Sources of GeV Photons and the Fermi Results

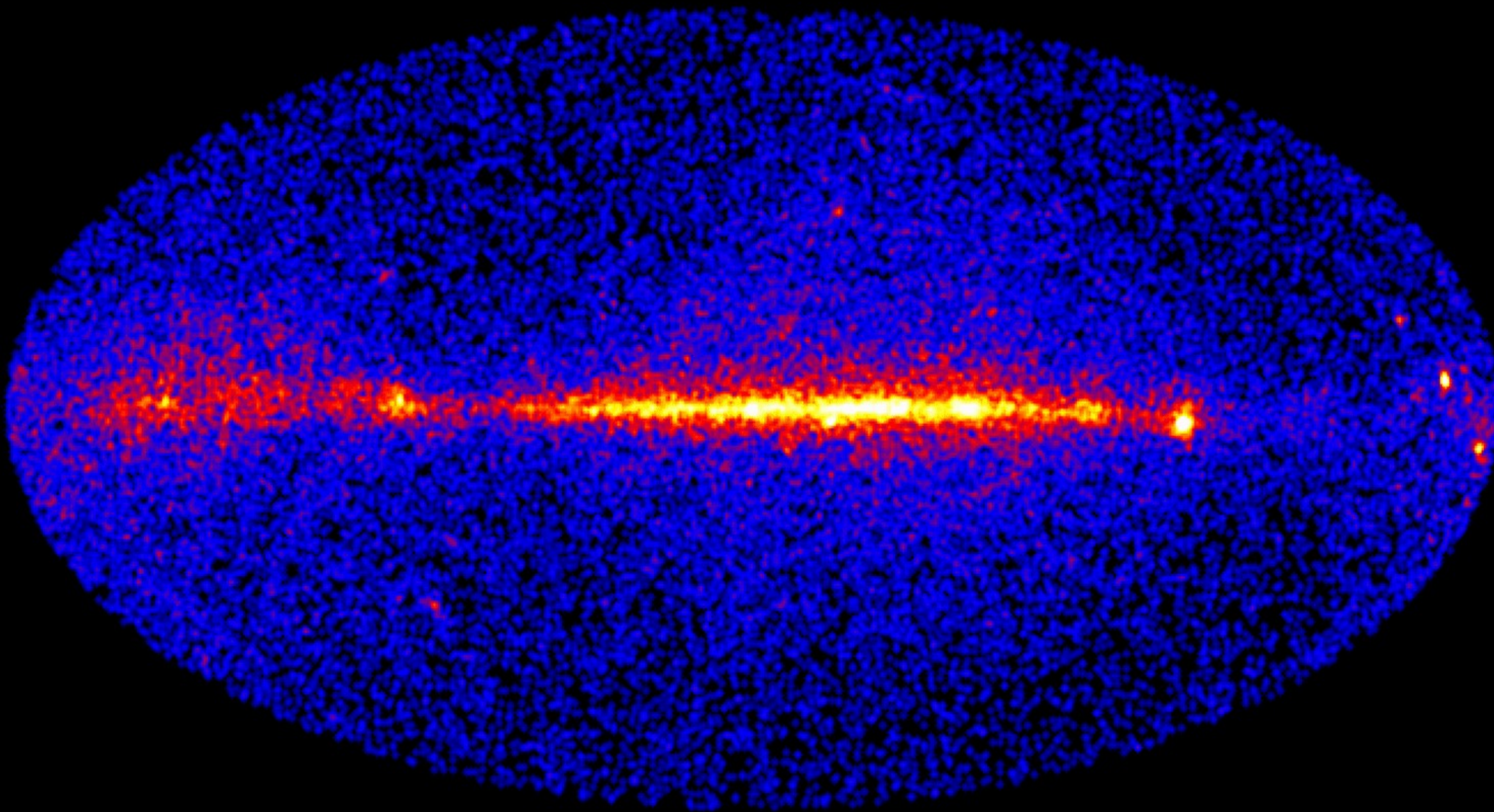
Chuck Dermer (NRL)

http://heseweb.nrl.navy.mil/gamma/~dermer/default.htm

1. GeV instrumentation and the GeV sky with the Fermi Gamma-ray Space Telescope
2. First Fermi Catalog of Gamma Ray Sources and the Fermi Pulsar Catalog
3. First Fermi AGN Catalog
4. **Relativistic jet physics and blazars**
5. $\gamma$ rays from cosmic rays in the Galaxy
6. $\gamma$ rays from star-forming galaxies and clusters of galaxies, and the diffuse extragalactic $\gamma$-ray background
7. Microquasars, radio galaxies, and the extragalactic background light
8. Fermi Observations of Gamma Ray Bursts
9. Fermi acceleration, ultra-high energy cosmic rays, and Fermi

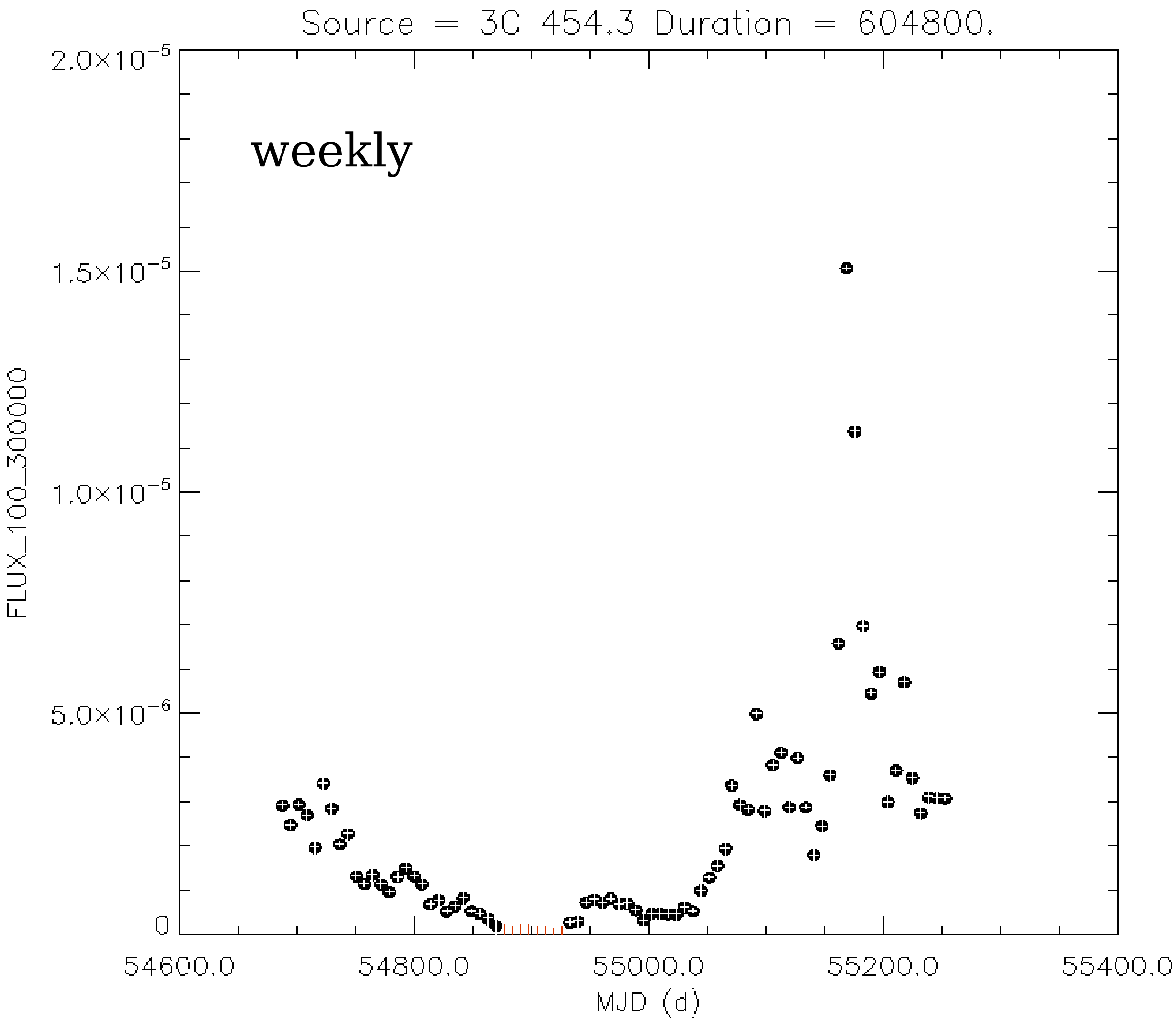
**Thanks to C.C. Cheung, J. Finke**

# Blazar 3C 454.3's Record Flare



November 3, 2009

# 3C 454.3 Light Curves

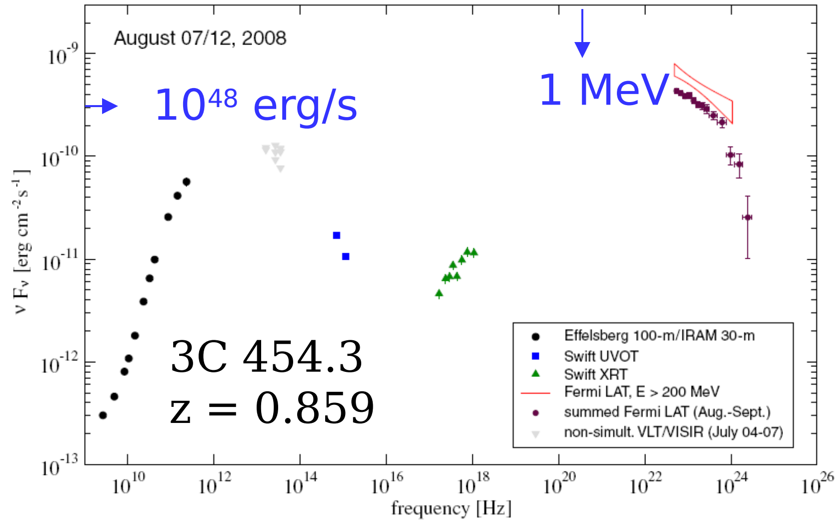


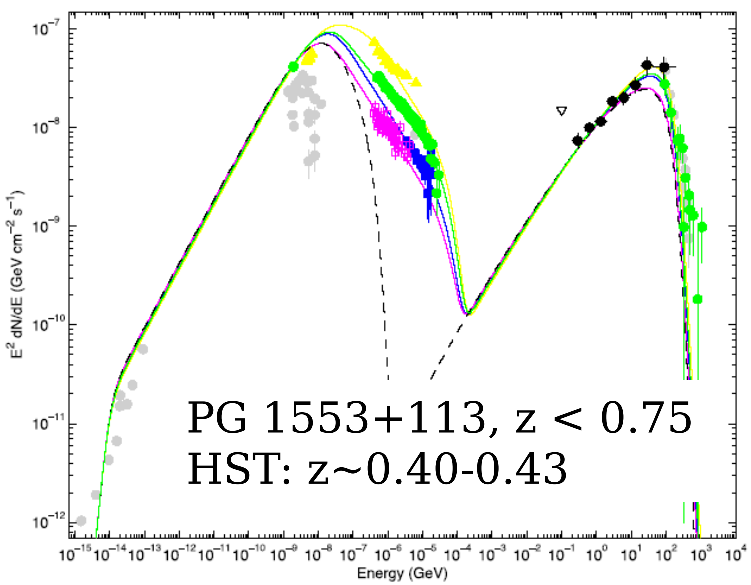
# Spectral Energy Distributions of Blazars

Preliminary (not for distribution)

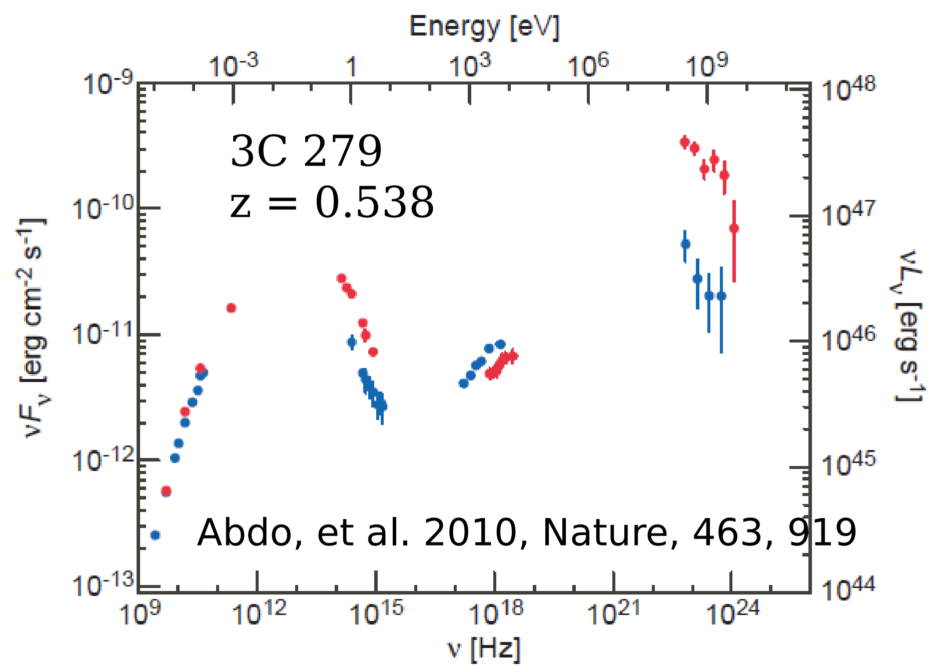
Mrk 501, z = 0.033

Abdo, et al. 2009, ApJ, 699, 817




Abdo, et al. 2010, ApJ, 708, 1310




Abdo, et al. 2010, Nature, 463, 919

## Demonstrations of Relativistic Outflows

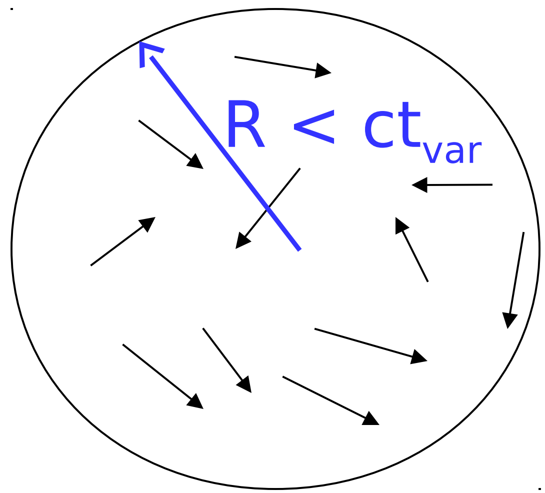
1. Compton catastrophe

2. Superluminal motion

3. $\gamma\gamma$ opacity argument

$$\gamma + \gamma' \rightarrow e^+ + e^-$$

$$\tau_{\gamma\gamma} \approx \sigma_{\gamma\gamma} n_\gamma R, \;\; \sigma_{\gamma\gamma} \approx \sigma_T$$




$$n_\gamma \approx \frac{L_\gamma}{4\pi R^2 c E_\gamma}$$

$$\tau_{\gamma\gamma} \approx \frac{\sigma_T L_\gamma}{4\pi m_e c^4 t_{\rm var}} \approx 1000 \frac{L_\gamma / (10^{48} erg/s)}{t_{\rm var}(day)}$$

3C 120

# Blazar Modeling

Nonthermal $\gamma$ rays $\Rightarrow$ relativistic particles + intense photon fields

**Leptonic jet model:**

Nonthermal synchrotron paradi

Associated SSC and EC compon

Location of emission site

**Hadronic jet model:**

Secondary nuclear production

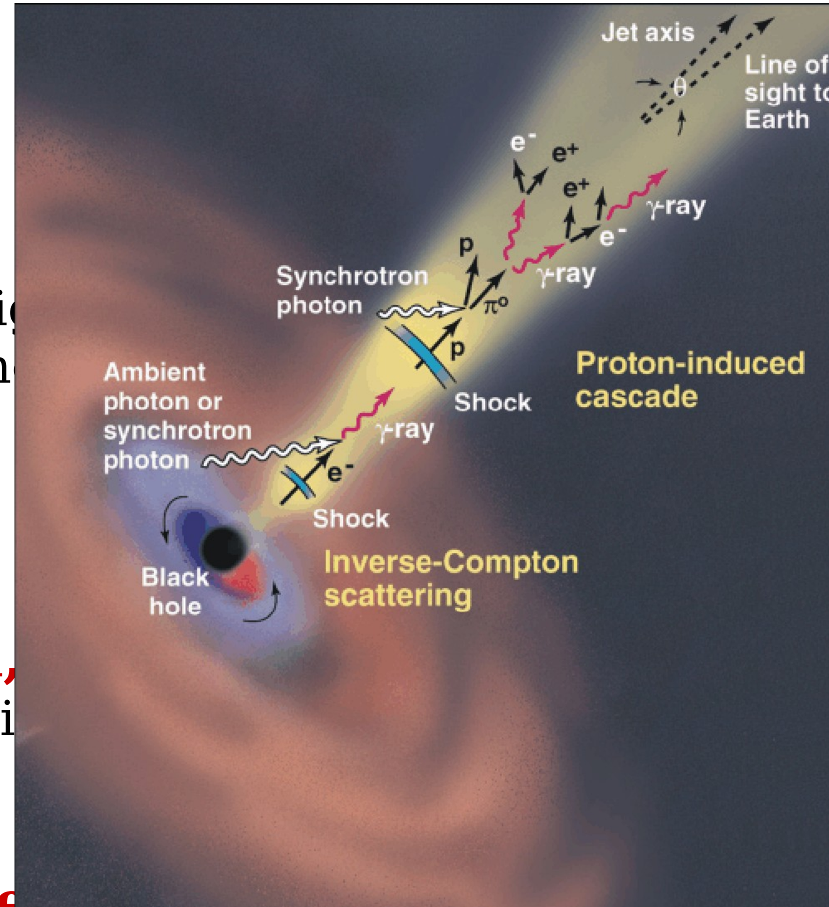
$\mathbf{pN \rightarrow \pi^o,\ \pi^\pm \rightarrow \gamma,\ \nu,\ n,}$

Proton and ion synchrotron radi

$\mathbf{pB \rightarrow \gamma}$

Photomeson production

$\mathbf{p\gamma \rightarrow \pi^o, \pi^\pm \rightarrow \gamma,\ \nu,\ n,\ e}$




High energy $\gamma$-ray component from $\mathbf{\gamma\gamma' \rightarrow e^\pm \rightarrow \gamma}$ by Compton or synchrotron processes

Neutrons escape to become UHECRs

# Black Hole Jet Physics: AGNs

**Synchrotron/Compton**
**Leptonic Jet Model**

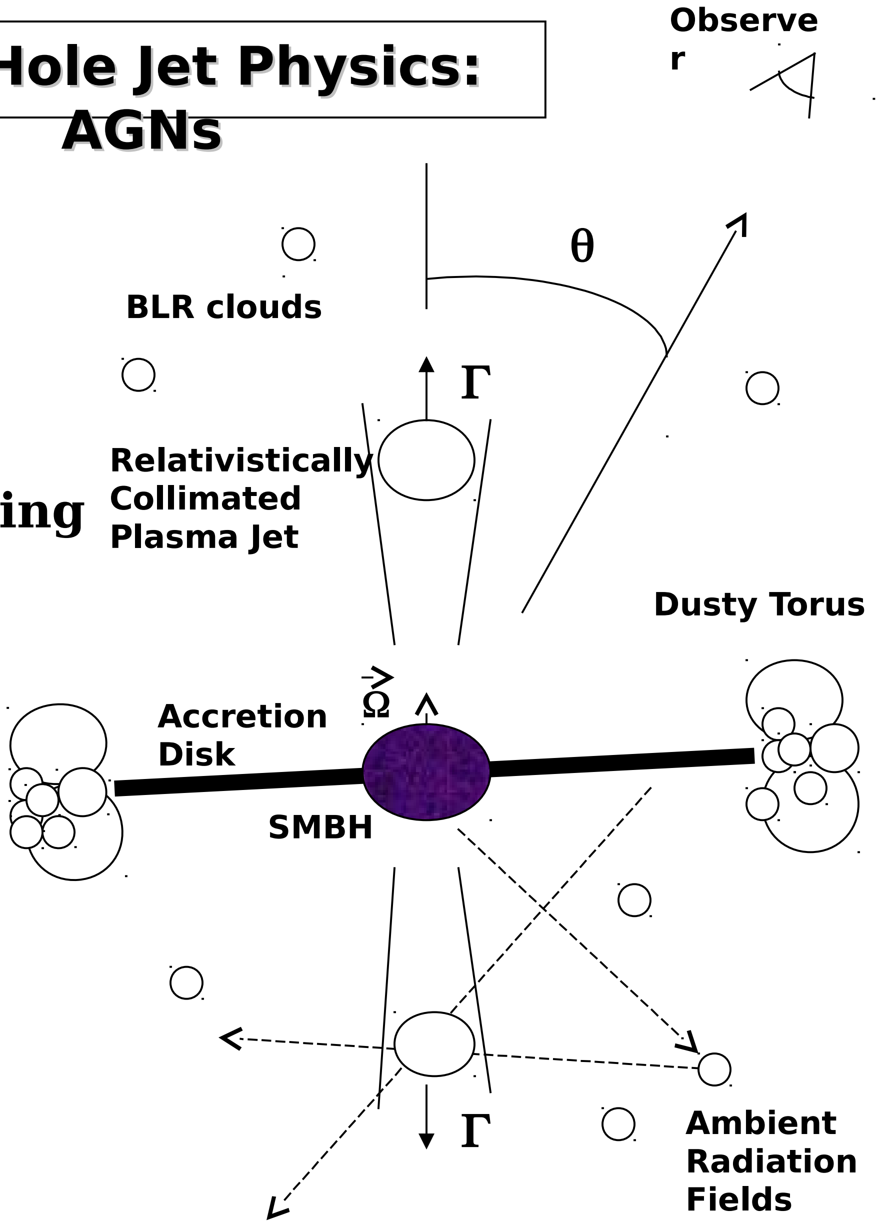
**BL Lac vs. FSRQs**
- Target photons for scattering
- Accretion regime

**Blob Formalism**

**Energy Sources:**
1. Accretion Power
2. Rotation Power

**Supermassive Black Holes**

Identifying hadronic emissions



# Doppler Factor

$$\delta_D \equiv [\Gamma(1-\beta\cos\theta)]^{-1}$$

$$\Delta x = \beta c \Delta t_* = \beta\Gamma c \Delta t'$$

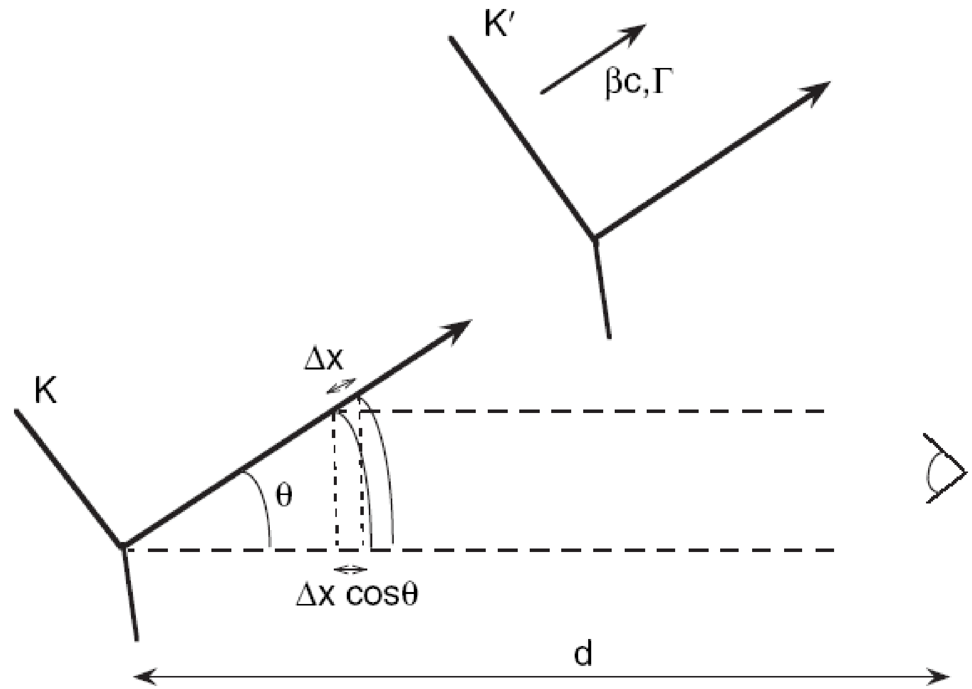
$$t = t_* + \frac{d}{c} - \frac{x\cos\theta}{c}$$

$$t + \Delta t = t_* + \Delta t_* + \frac{d}{c} - \frac{(x+\Delta x)\cos\theta}{c}$$

$$\Rightarrow \Delta t = \frac{\Delta x}{\beta c}(1-\beta\cos\theta) = \Gamma\Delta t'(1-\beta\cos\theta)$$

$$\Rightarrow \Delta t = \frac{\Delta t'}{\delta_D}$$

$$\theta = 0 \Rightarrow \Delta t = \frac{\Delta x}{\beta c}(1-\beta) \rightarrow \frac{\Delta x}{\Gamma^2 c}$$




$$dt = \frac{(1+z)dt'}{\delta_D}$$

$$\varepsilon = \frac{\delta_D \varepsilon'}{(1+z)}$$

# Variability and Source Size

Source size from direct observations:

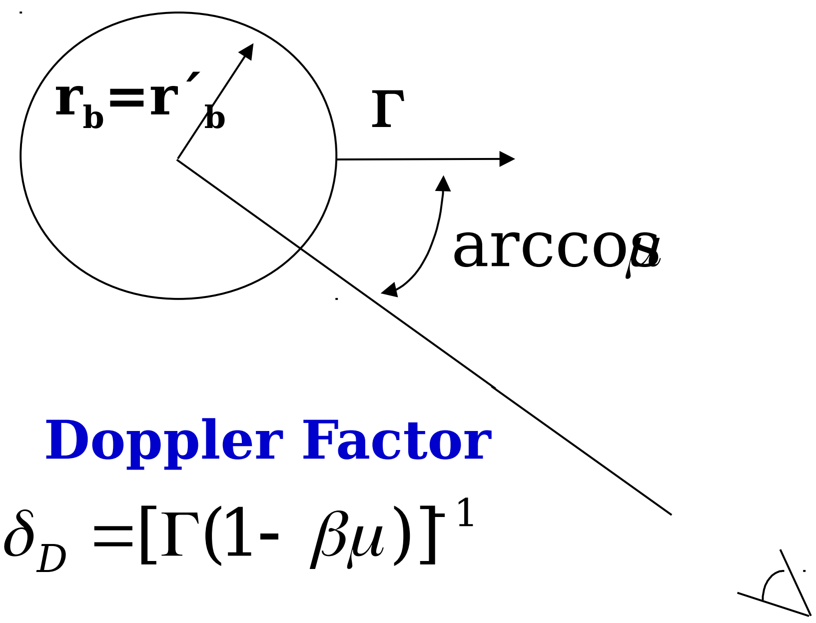
$$r'_b \cong d_A \vartheta \cong 2\left(\frac{d_A}{10^{27}\,cm}\right)\vartheta(mas)\; pc$$

Source size from temporal variability:

$$r'_b \lesssim c t'_{var} = c\delta_{\rm D} t_{var}/(1+z)$$

$$r'_b(cm) < \frac{2.5\times 10^{15}\delta_D t_{\rm var}(day)}{(1+z)}$$

**Spherical blob in comoving frame**




**Doppler Factor**

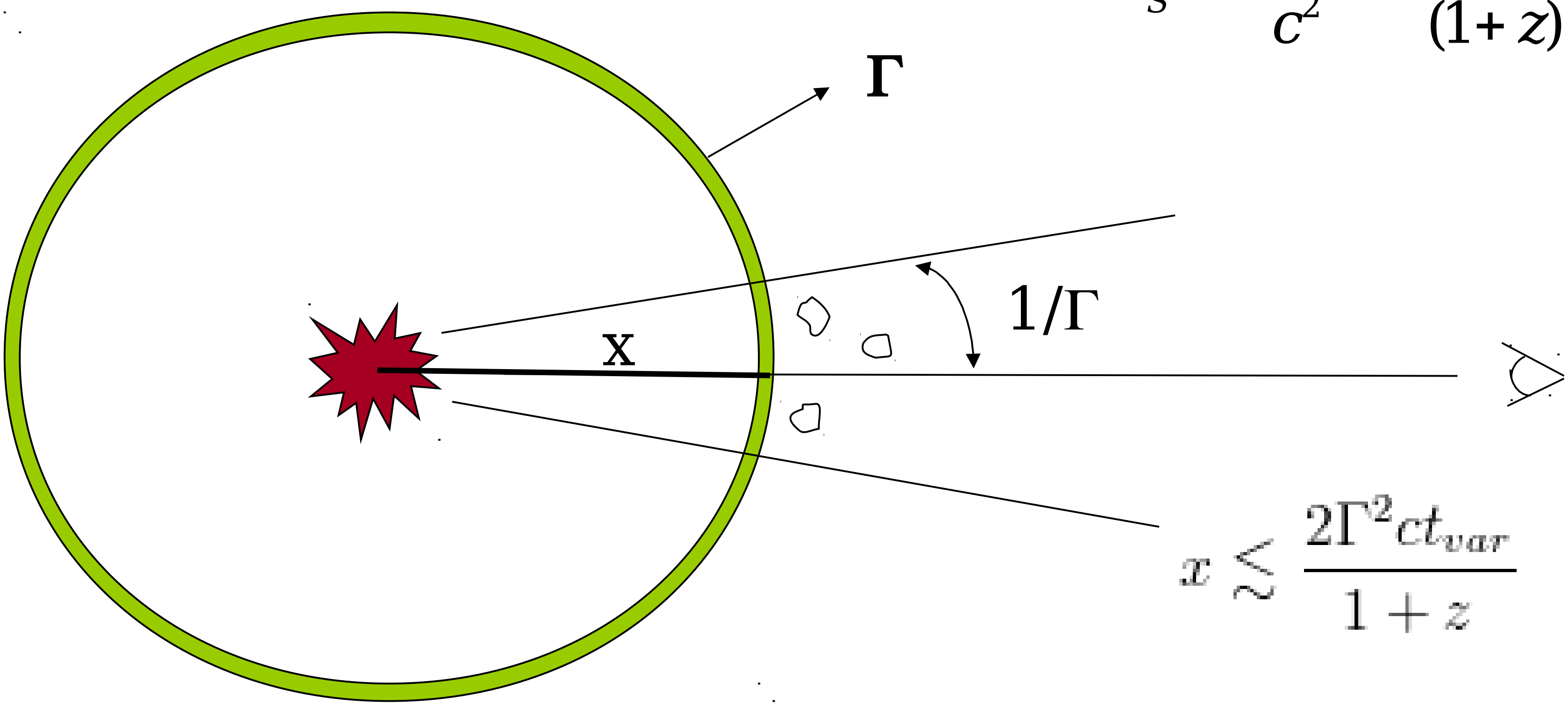
$$\delta_D = [\Gamma(1-\beta\mu)]^{-1}$$

Variability timescale implies maximum emission region size scale

# Variability and Source Location

$$c\Delta t/(1+z) \cong x(1-\cos\theta) \cong x\theta^2/2 \cong x/2\Gamma^2$$
$$\Rightarrow x \cong 2\Gamma^2 c\Delta t/(1+z)$$

$$R_S = \frac{2GM}{c^2} < \frac{ct_{\mathrm{var}}}{(1+z)}$$



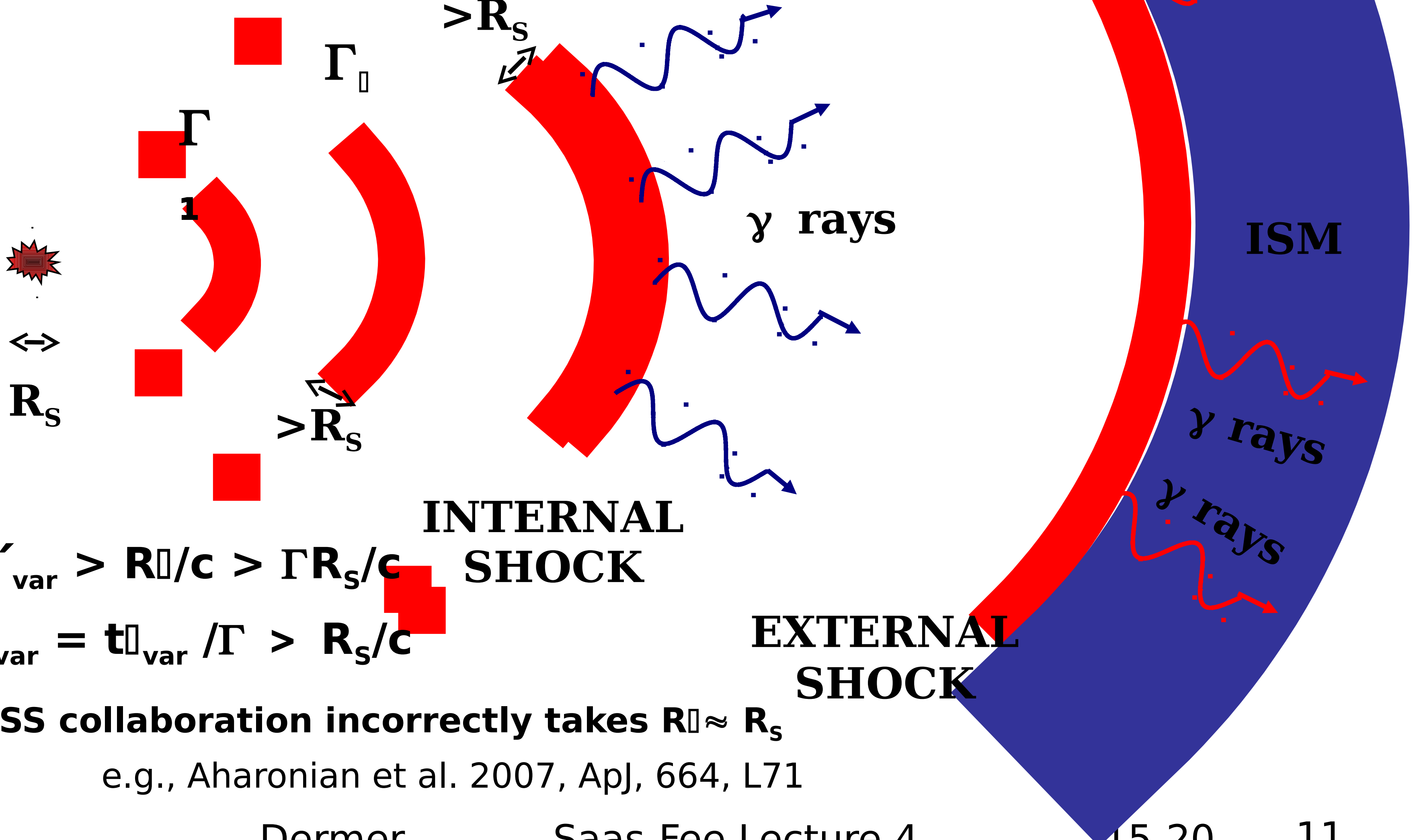

$$x \lesssim \frac{2\Gamma^2 ct_{var}}{1+z}$$

Variability timescale implies engine size scale, comoving size scale factor ≈Γ larger and emission location ~$\Gamma^2$ larger than values inferred for stationary region

Rapid variability by energizing regions within the Doppler cone

# Temporal Variability

**Size scale in stationary frame: $R > R_S$**
**Size scale in comoving frame: $R' = \Gamma R > \Gamma R_S$**
**(Lorentz contracted to size R in stationary frame)**




$t'_{var} > R'/c > \Gamma R_S/c$

$t_{var} = t'_{var}/\Gamma > R_S/c$

**HESS collaboration incorrectly takes $R' \approx R_S$**

e.g., Aharonian et al. 2007, ApJ, 664, L71

# Energy Fluxes, Blobs and Blast Waves

Measured: **z** (⇒ $d_L$), **$\nu F_\nu$** flux, **$t_v$** and jet angle **$\theta_j$** for blob model

**Total Energy Flux:** $\Phi = \dfrac{dE}{dAdt} = \dfrac{L}{4\pi d_L^2}$

**Spectral Energy Flux:**

$$f_\varepsilon (erg\,cm^{-2}\,s^{-1}) = \nu F_\nu$$

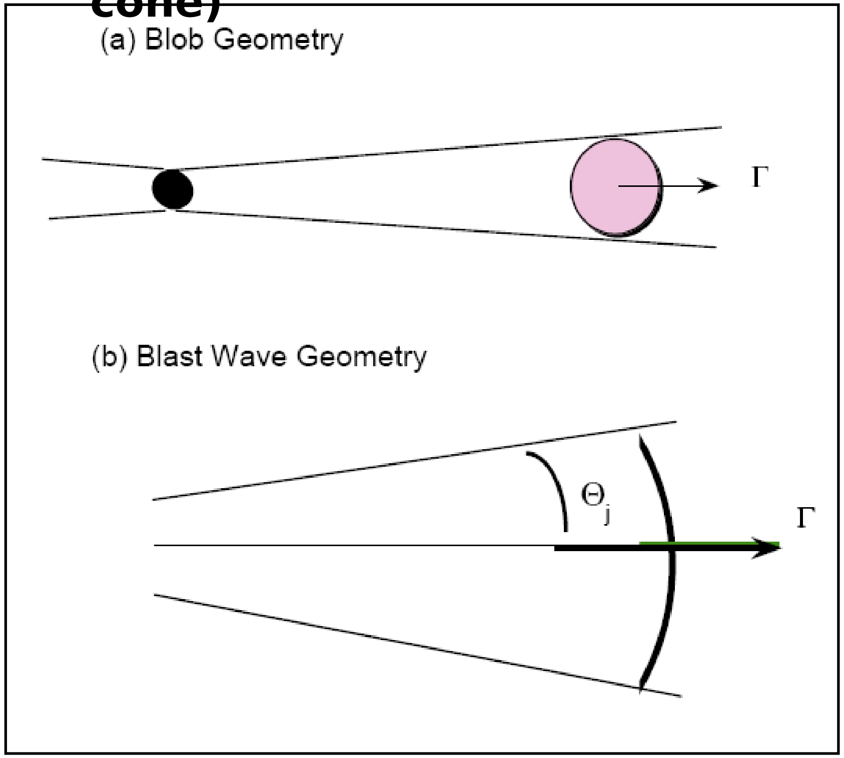
$$Blob: \Phi \approx \delta_D^4 \frac{L'_\gamma}{4\pi d_L^2}$$

$$f_\varepsilon = \nu F_\nu = \frac{\delta_D^4 \varepsilon' L'(\varepsilon')}{4\pi d_L^2}, \; r'_b = \frac{c\delta_D t_v}{1+z}$$

$$Blast\ Wave: \Phi \approx \Gamma^2 \frac{L'_\gamma}{4\pi d_L^2}$$

$$f_\varepsilon = \nu F_\nu = \frac{\Gamma^2 \varepsilon' L'(\varepsilon')}{4\pi d_L^2}, \; R = \frac{c\Gamma^2 t_v}{1+z}, \; R' = R/\Gamma$$

**Blob (off-axis jet model) vs. Blast Wave (observer within jet cone)**




Blob and blast wave framework are equivalent for opacity calculations

# Internal Radiation Fields

Instantaneous energy flux $\Phi$ (erg cm$^{-2}$ s$^{-1}$); variability time $t_v$, redshift z

Blob:

$$\Phi \approx \delta_D^4 \frac{L'_\gamma}{4\pi d_L^2}, \quad u'_\gamma \sim \frac{L' t'_{esc}}{V'} \sim \frac{3 d_L^2 \Phi}{\delta_D^4 r'^2 c}, \quad t'_{esc} \sim r'/c \sim \Delta t' \approx \frac{\delta_D t_v}{1+z}$$

$$u'_\gamma \approx \frac{3 d_L^2 (1+z)^2 \Phi}{\delta_D^6 t_v^2 c^3} \qquad or\ n'_\gamma(\epsilon') \cong \frac{3 d_L^2 (1+z)^2 f_\epsilon}{m_e c^5 \epsilon'^2 \delta_D^6 t_v^2}$$

$$n'_{ph}(\epsilon') \cong \frac{3 d_L^2 f_\epsilon}{m_e c^3 \epsilon'^2 \delta_D^4 r'^2} \qquad r' \approx \frac{c \delta_D t_v}{1+z}, \quad \epsilon' \cong \frac{(1+z)\epsilon}{\delta_D}$$

Blast Wave:

$$u'_\gamma \cong \frac{4\pi d_L^2 \Phi}{4\pi R^2 \Gamma^2 c} \cong \frac{d_L^2 (1+z)^2 \Phi}{\Gamma^6 t_v^2 c^3} \quad or\ n'_\gamma(\epsilon') \cong \frac{d_L^2 (1+z)^2 f_\epsilon}{m_e c^5 \epsilon'^2 \Gamma^6 t_v^2}$$

$$R' = R/\Gamma, R = \frac{c \Gamma^2 t_v}{1+z}, \quad \epsilon' \cong \frac{(1+z)\epsilon}{\Gamma}$$

# Internal Magnetic Fields and Power

Internal energy density $u' = u'_\gamma/\varepsilon_e$ implies a jet magnetic field

$$B' \cong \sqrt{8\pi\varepsilon_B u'_\gamma / \varepsilon_e}$$

$\varepsilon_e$ is fraction of total energy density in nonthermal electrons assumed to be producing the $\gamma$ rays

$\varepsilon_B$ is fraction of total energy density in magnetic field

Apparent Jet Power

$$P_j = 4\pi R^2 \beta c \Gamma^2 (u'_B + u'_{par} + u'_\gamma)$$

Absolute Jet Power

$$r'_b \approx \frac{c\delta_D t_v}{1+z}$$

$$P_j = 2\pi r_b'^2 \beta c \delta_D^2 \left(\frac{\Gamma^2}{\delta_D^2}\right)(u'_B + u'_{par} + u'_\gamma)$$

# $\gamma\gamma$ Opacity

The absorption probability per unit pathlength is

$$\frac{d\tau_{\gamma\gamma}(\epsilon_1)}{dx} = \frac{\dot{N}_{sc}}{c} = \oint d\Omega\,(1-\mu)\int_0^\infty d\epsilon\; n_{ph}(\epsilon,\Omega)\,\sigma_{\gamma\gamma}(s)\;,$$

from eq. (2.40), where $\dot{N}_{sc}$ is the $\gamma$-ray absorption rate, and the dependence on $\epsilon_1$ is contained in the definition of $s$, eq. (10.3). For an *isotropic* photon field,

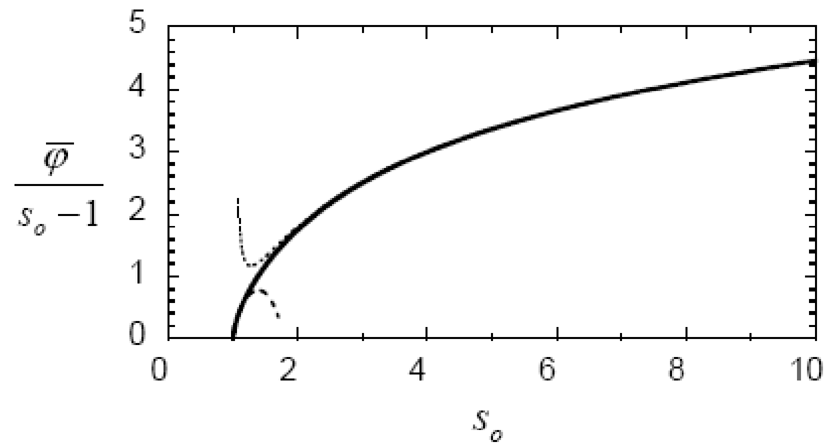
$$\frac{d\tau_{\gamma\gamma}}{dx} = \frac{1}{2}\int_{-1}^{1} d\mu\,(1-\mu)\int_0^\infty d\epsilon\; n_{ph}(\epsilon)\,\sigma_{\gamma\gamma}(s)\;.$$

This can be written [243, 244, 245] in the form

$$\frac{d\tau_{\gamma\gamma}}{dx} = \frac{\pi r_e^2}{\epsilon_1^2}\int_{1/\epsilon_1}^\infty d\epsilon\;\epsilon^{-2}\;n_{ph}(\epsilon)\;\bar{\varphi}(s_0)\;,$$

where $s_0 \equiv \epsilon\epsilon_1$, and

$$\bar{\varphi}(s_0) = 2\int_1^{s_0} ds\;\frac{s\sigma_{\gamma\gamma}(s)}{\pi r_e^2}$$



# $\gamma\gamma$ Opacity: $\delta$-function approximation

In cases where the external radiation can be approximated as isotropic, a mean interaction takes place with $\theta \simeq \pi/2$ or $\mu = 0$. In this case, we can write

$$\frac{d\tau_{\gamma\gamma}}{dx} \cong \int_{2/\epsilon_1}^{\infty} d\epsilon\, \sigma_{\gamma\gamma}(\epsilon_1\epsilon) n_{ph}(\epsilon; x) \ . \qquad (10.31)$$

Given this assumption, the simplest invariant cross section that can be formed from the (quasi-)invariant $\epsilon\epsilon_1$ is

$$\sigma_{\gamma\gamma}(\epsilon\epsilon_1) \cong \frac{2}{3}\sigma_{\rm T}\, \delta(\epsilon\epsilon_1 - 2) \cong \frac{2}{3}\frac{\sigma_{\rm T}}{\epsilon_1}\, \delta(\epsilon - \frac{2}{\epsilon_1}) \cong \frac{1}{3}\, \sigma_{\rm T}\, \epsilon\, \delta(\epsilon - \frac{2}{\epsilon_1}) \qquad (10.32)$$

[250], where the coefficient improves comparison with numerical results.

The photoabsorption optical depth for a $\gamma$-ray photon with energy $\epsilon_1$ in a radiation field with spectral photon density $n_{ph}(\epsilon', \mu'; r')(\simeq n_{ph}(\epsilon')/2$ for a uniform isotropic radiation field in the comoving frame) is [244]

$$\tau_{\gamma\gamma}(\epsilon_1') = \int_{r_1'}^{r_2'} dr' \int_{-1}^{1} d\mu'(1-\mu') \int_{2/\epsilon_1'(1-\mu')}^{\infty} d\epsilon'\ \sigma_{\gamma\gamma}[\epsilon'\epsilon_1'(1-\mu')] n_{ph}(\epsilon', \mu'; r')$$

$$\cong r_b' \int_0^{\infty} d\epsilon'\ \sigma_{\gamma\gamma}(\epsilon', \epsilon_1')\, n_{ph}'(\epsilon'). \qquad (10.33)$$

# $\gamma\gamma$ Opacity : $\delta$-function approximation for Blob

$$\frac{d\tau_{\gamma\gamma}(\epsilon_1')}{dx'} \cong \int_0^\infty d\epsilon' \sigma_{\gamma\gamma}(s') n'_{ph}(\epsilon'), \quad \sigma_{\gamma\gamma}(s') \cong \frac{2}{3}\sigma_T \delta(s' - 2)$$

$$\tau_{\gamma\gamma}(\epsilon_1') \approx \frac{2}{3}\sigma_T r' \int_0^\infty d\epsilon' \frac{\delta(\epsilon' - 2/\epsilon_1')}{\epsilon_1'} n'_{ph}(\epsilon') \qquad \epsilon' = 2/\epsilon_1'$$

$$\approx \frac{2}{3}\frac{\sigma_T r' n'_{ph}(2/\epsilon_1')}{\epsilon_1'} \qquad n'_{\gamma}(\epsilon') \cong \frac{3 d_L^2 (1+z)^2 f_\epsilon}{m_e c^5 \epsilon'^2 \delta_D^6 t_v^2}$$

$$n'_{ph}(\epsilon') \cong \frac{3 d_L^2 f_\epsilon}{m_e c^3 \epsilon'^2 \delta_D^4 r'^2} \quad \Rightarrow \tau_{\gamma\gamma}(\epsilon_1') \cong \frac{2\sigma_T}{3\epsilon_1'} \frac{3 d_L^2 f_\epsilon}{m_e c^3 \epsilon'^2 \delta_D^4 r'}$$

$$\epsilon' = \frac{(1+z)\epsilon}{\delta_D}$$

# Minimum Doppler factor approximation for Blob

$$\tau_{\gamma\gamma}(\varepsilon_1') \cong \frac{2\sigma_T}{\varepsilon_1'}\,\frac{d_L^2 f_\varepsilon}{m_e c^3 \varepsilon'^2 \delta_D^4 r'}$$

$$\varepsilon' = 2/\varepsilon_1'$$

$$\varepsilon_1' = \frac{(1+z)\varepsilon_1}{\delta_D}$$

$$\tau_{\gamma\gamma}(\varepsilon_1') \cong \frac{\sigma_T}{2}\,\frac{d_L^2 f_\varepsilon \varepsilon_1'}{m_e c^3 \delta_D^4 r'}$$

$$r' \approx \frac{c\delta_D t_v}{1+z},$$

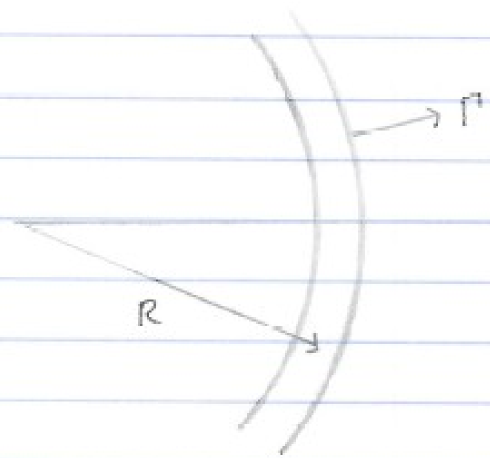
$$\tau_{\gamma\gamma}(\varepsilon_1) \cong \frac{\sigma_T (1+z)^2 d_L^2 f_{\hat\varepsilon} \varepsilon_1}{2 m_e c^4 \delta_D^4 t_v}$$

Minimum bulk Lorentz factor: $\tau_{\gamma\gamma}(\varepsilon_1) = 1$

$$\Rightarrow\ \delta_{D,\min} \cong \left[\frac{\sigma_T (1+z)^2 d_L^2 f_{\hat\varepsilon} \varepsilon_1}{2 m_e c^4 t_v}\right]^{1/6}$$

$$\varepsilon' \varepsilon_1' \approx 2 \Rightarrow\ \hat\varepsilon \cong \frac{2\delta_D^2}{(1+z)^2 \varepsilon_1}$$

## $\gamma\gamma$ Opacity : $\delta$-function approximation for Blast Wave




$$\Phi = \frac{L_*}{4\pi d_L^2}$$

$$L_* = \frac{d\mathcal{E}_*}{dt_*} = \Gamma^2 \frac{d\mathcal{E}'}{dt'} = \Gamma^2 L', \quad \mathcal{E}_* = \Gamma \mathcal{E}', \quad dt_* = dt'/\Gamma$$

$$\therefore \quad f_\epsilon \approx \frac{\Gamma^2 \epsilon' L'(\epsilon)}{4\pi d_L^2} \quad \text{or} \quad \epsilon' L'(\epsilon') = \frac{4\pi d_L^2 f_\epsilon}{\Gamma^2}, \quad \epsilon' = \frac{(1+z)\epsilon}{\Gamma}$$

$$\frac{\epsilon' L'(\epsilon')}{4\pi R^2 c\, m_e c^2 \epsilon'^2} = n'(\epsilon') = \frac{d_L^2 f_\epsilon}{R^2 \Gamma^2 m_e c^3 \epsilon'^2}$$

$$R \cong \Gamma^2 c\, t_v/(1+z), \quad \Delta R' \cong R/\Gamma$$

$$\tau_{\gamma\gamma}(\epsilon_1') \cong \frac{2}{3}\, \frac{\Delta R' \sigma_T\, n'(2/\epsilon_1')}{\epsilon_1'}$$

# Minimum Doppler factor approximation for Blast Wave

$$\tau_{\gamma\gamma}(\epsilon_1') \simeq \frac{2}{3}\,\frac{\Delta R' \sigma_T\, n'(2/\epsilon_1')}{\epsilon_1'}$$

$$= \frac{2}{3}\,\frac{\cancel{R}}{\Gamma}\,\frac{\sigma_T}{\cancel{\epsilon_1'}}\,\frac{d_L^2 f_\epsilon}{R^{\cancel{2}}\Gamma^2 m_e c^3 \epsilon_1'^{\cancel{2}}} = \frac{\sigma_T d_L^2 f_\epsilon \epsilon_1'}{2\cdot 3\Gamma^3 R\, m_e c^3}\,, \quad \epsilon_1' = \frac{(1+z)\epsilon_1}{\Gamma}$$

$$\tau_{\gamma\gamma}(\epsilon_1) = \frac{\sigma_T (1+z)^2 d_L^2 f_\epsilon \epsilon_1}{6\,\Gamma^6 t_v m_e c^4}$$

$$\tau_{\gamma\gamma}(\epsilon_1) = 1 \Rightarrow \quad \Gamma_{min} = \left[\frac{\sigma_T (1+z)^2 d_L^2 f_{\hat\epsilon}\, \epsilon_1}{6\, t_v m_e c^4}\right]^{1/6}$$

$$\epsilon'\epsilon_1' = 2 \;\Rightarrow\; \hat\epsilon = \frac{2\Gamma^2}{(1+z)^2\epsilon_1}$$

$$\delta_{D,\min} \cong \left[\frac{\sigma_T (1+z)^2 d_L^2 f_{\hat\varepsilon}\, \varepsilon_1}{2 m_e c^4 t_v}\right]^{1/6}$$

$$3^{1/6} \cong 1.2009\ldots$$

# $\gamma\gamma$ opacity and $\Gamma_{min}$ for PKS 2155-304

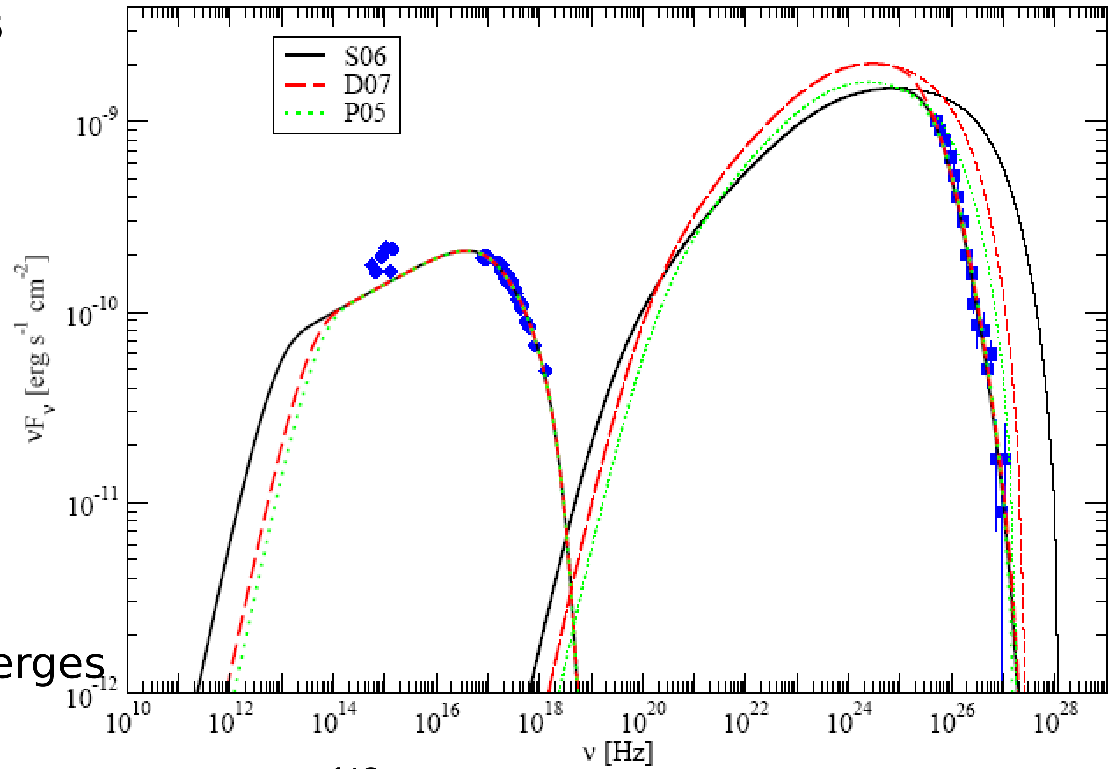
$$\delta_{D,\min} \cong \left[\frac{\sigma_T (1+z)^2 d_L^2 f_{\hat{\epsilon}} \epsilon_1}{2 m_e c^4 t_v}\right]^{1/6}$$

$$\hat{\epsilon} \cong \frac{2\delta_D^2}{(1+z)^2 \epsilon_1}$$

$z = 0.116$, $d_L = 1.65\times10^{27}$ cm

$t_v = 300\ t_{5m}$ s

Solve iteratively, quickly converges




$$\delta_{D,\min} \cong 32\left[\frac{(f_{\hat{\epsilon}}/10^{-10} erg\, s^{-1} cm^{-2}) E_1(TeV)}{t_{5m}}\right]^{1/6}$$

$$\hat{E}(keV) \cong 0.6\frac{(\delta_D/30)^2}{E_1(TeV)}$$

- Code of Finke et al. (2008)
- Includes internal $\gamma\gamma$ opacity but not pair reinjection
- Sensitive to EBL model
- Fit to 2006 flare

# Synchrotron Self-Compton Model

Basic tool is one-zone synchrotron/SSC model with synchrotron self-absorption and internal pair production

Even this lacks pair reinjection; multiple self-Compton components

Deducing source redshift from high-energy spectra requires both good spectral model and good EBL model

What portion of synchrotron spectrum should be fitted?

Synchrotron/SSC model: Best fit model; parameter studies; extracting underlying electron distribution; variability analysis

# Synchrotron/SSC Modeling

Approximations (in the one-zone model)

1. $\delta$-function approximation

zero-fold for synchrotron; 1 fold for SSC

Take KN effects into account by terminating integration when scattering enters the KN regime

Useful for analytic results; equipartition estimates; jet power calculations

2. Uniform approximation: B, $\delta_D$, and R’

a. Integrate elementary synchrotron emissivity over electron $\gamma$-factor distribution (assumed uniform throughout sphere)

b. Average synchrotron spectrum over blob to get target photon spectrum

c. Compton-scatter synchrotron photons using (isotropic) Jones formula, valid throughout Thomson and KN regimes

Provides accurate absolute power estimates (photon, particle, B-field)

given observing angle

for blazars, $\Gamma \approx \delta_D$; for radio galaxies inferred from

# Fitting Routine

**Code written by Justin Finke**

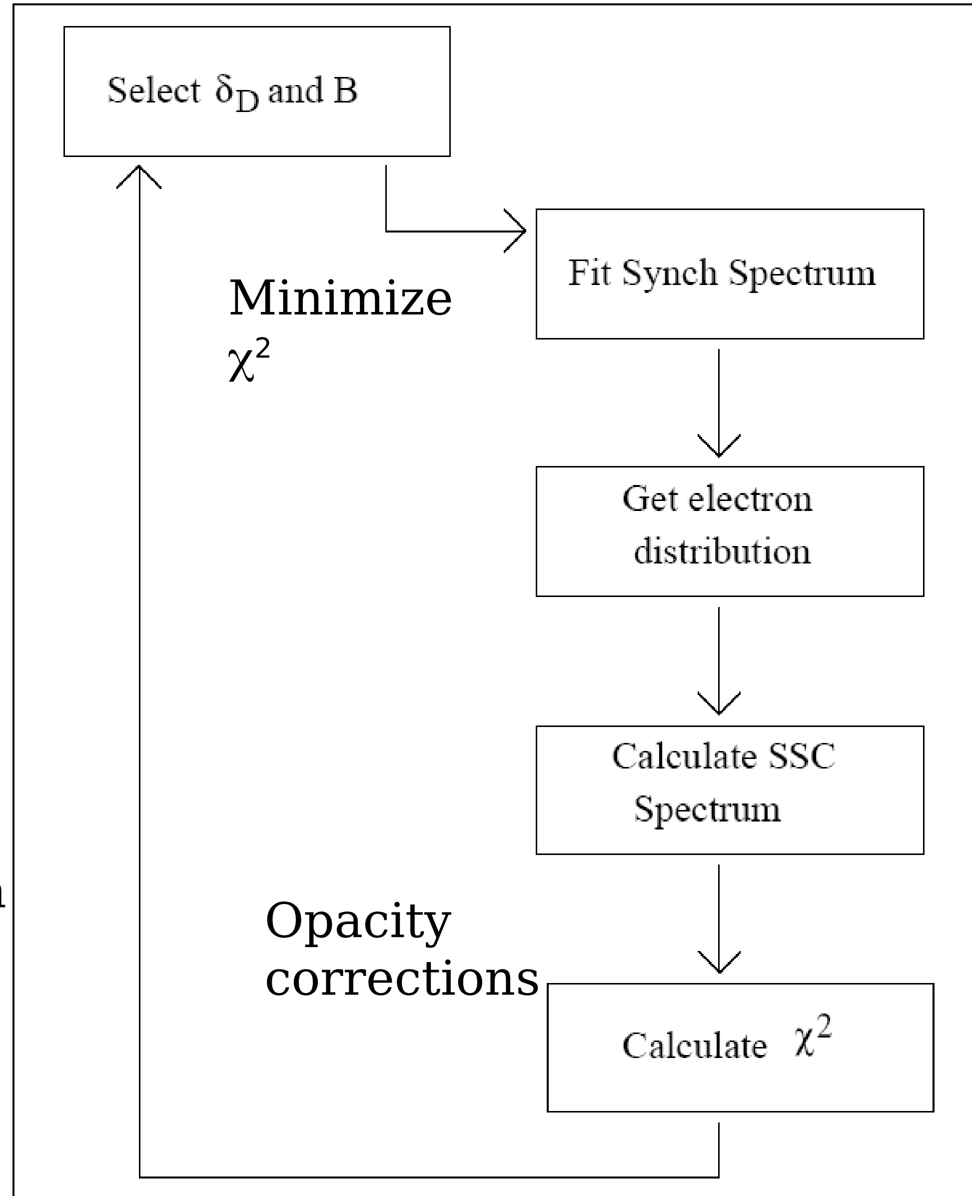
Write SSC as a function of: $\delta_D$, B, $r_b'$, z, $N_e(\gamma)$.

Use electron spectrum to calculate SSC using Jones (1968) formula

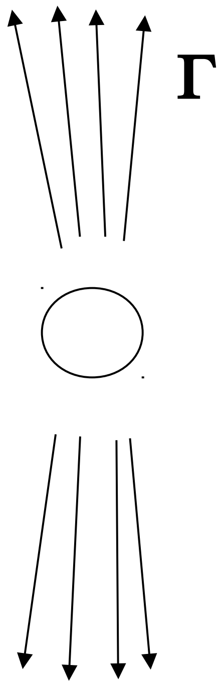
$\nu F_\nu^{syn}$ gives $N_e(\gamma)$ (CS86 expression)

Internal and EBL absorption calculated

Leaves two unknowns to fit: $\delta_D$ and B



# Jet Power




$$\boxed{n_* = \frac{L^*_{j,ke}}{2\Omega_j R^2 (\Gamma m_e c^2)\beta c} = n'(\langle\gamma\rangle + \chi m_p/m_e)}$$

$$\boxed{L^*_B = 2\Omega_j c R^2 \beta \Gamma^2 (\frac{B^2}{8\pi})}$$

Total jet power = sum of particle kinetic and magnetic field

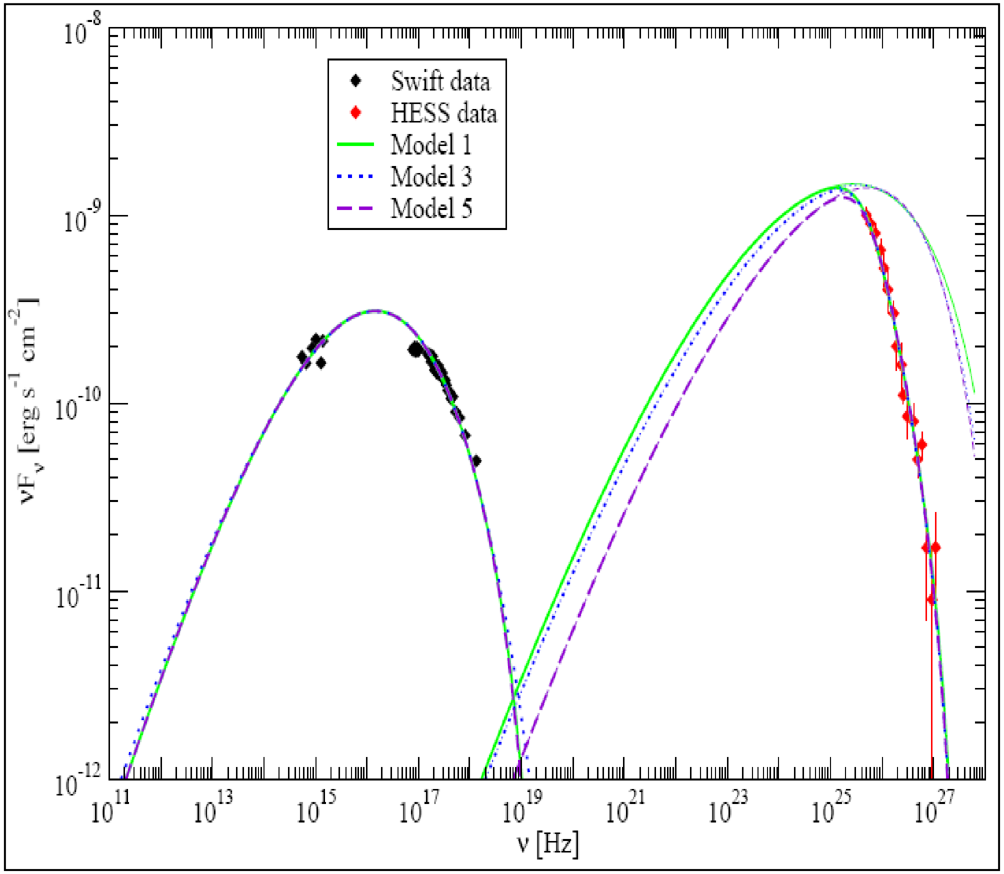
Minimum jet power for equipartition (minimum energy) magnetic field

Minimize jet power for measured synchrotron flux

- Jet power: total power available in jet (in observer frame)
- $L_j = 2\pi r_b'\beta\Gamma^2 c(u'_B + u'_p)$ (Celotti & Fabian 1993)
- $dL_j / dB = 0 \rightarrow B_{min}$ (equipartition)
- $B < B_{min} \rightarrow u'_p >> u'_B$ and $f_{SSC} > f_{syn}$

Synchrotron spectrum implies minimum jet power; additionally fitting $\gamma$ rays gives deviation of model from minimum jet power

# Results




**HESS data: 28 July, 2007**
**Swift data: 30 July 2007**

| Model | $\delta_D$ | B [mG] | $t_{var}$ [s] | $L_j$ [$10^{47}$ erg s$^{-1}$] |
|---|---|---|---|---|
| 1 | 872 | 2.7 | 30 | 4.4 |
| 3 | 367 | 3.6 | 300 | 2.7 |
| 5 | 185 | 2.7 | 3000 | 2.1 |

$\gamma'_{min} = 1$

Using EBL of Stecker et al. (2006).

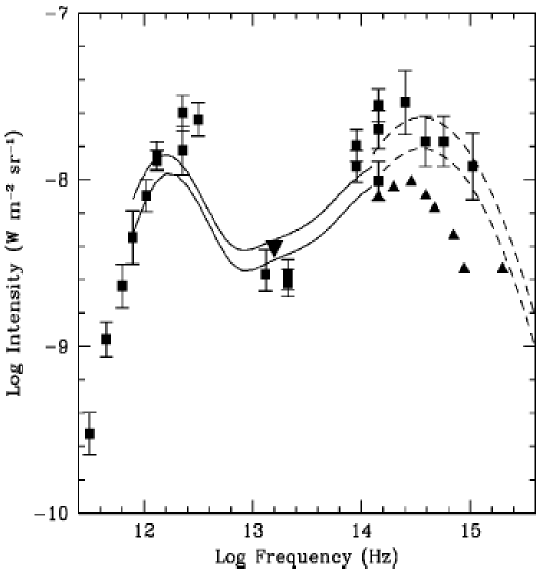
Unreasonably high $\delta_D$ and $L_j$.

$L_{Edd} = 10^{47}$ erg s$^{-1}$
From radio obs., $\delta_D < 10$

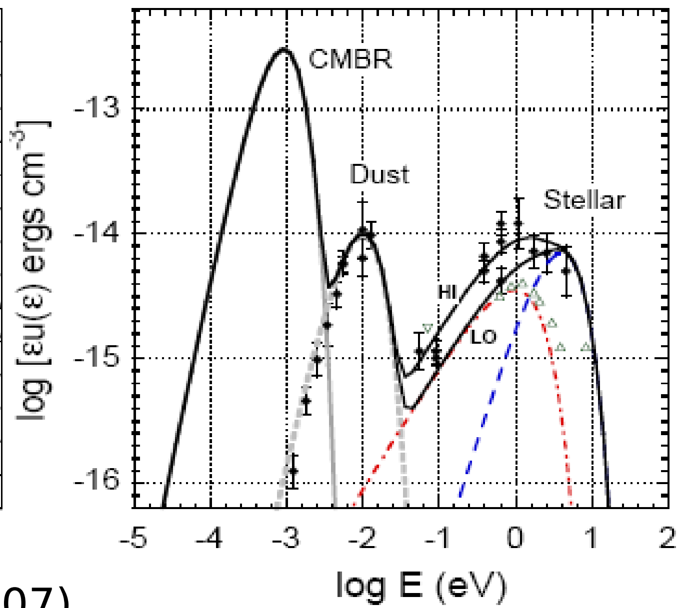
See Finke et al., ApJ, 686, 181 (2008), ApJ, for details

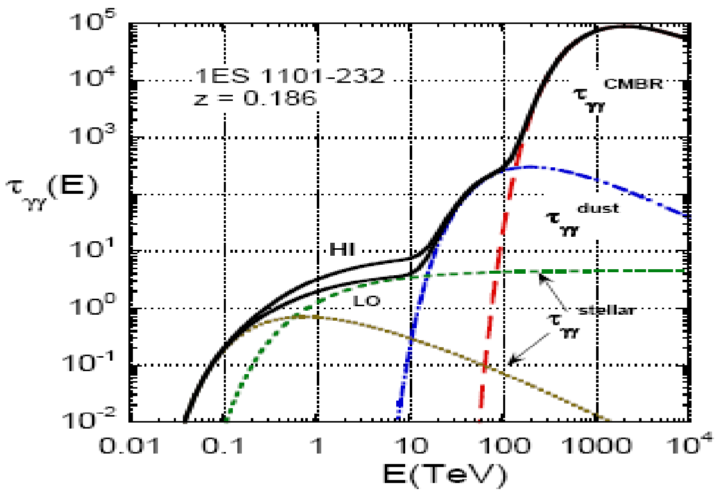
Can a lower IBL resolve problem?

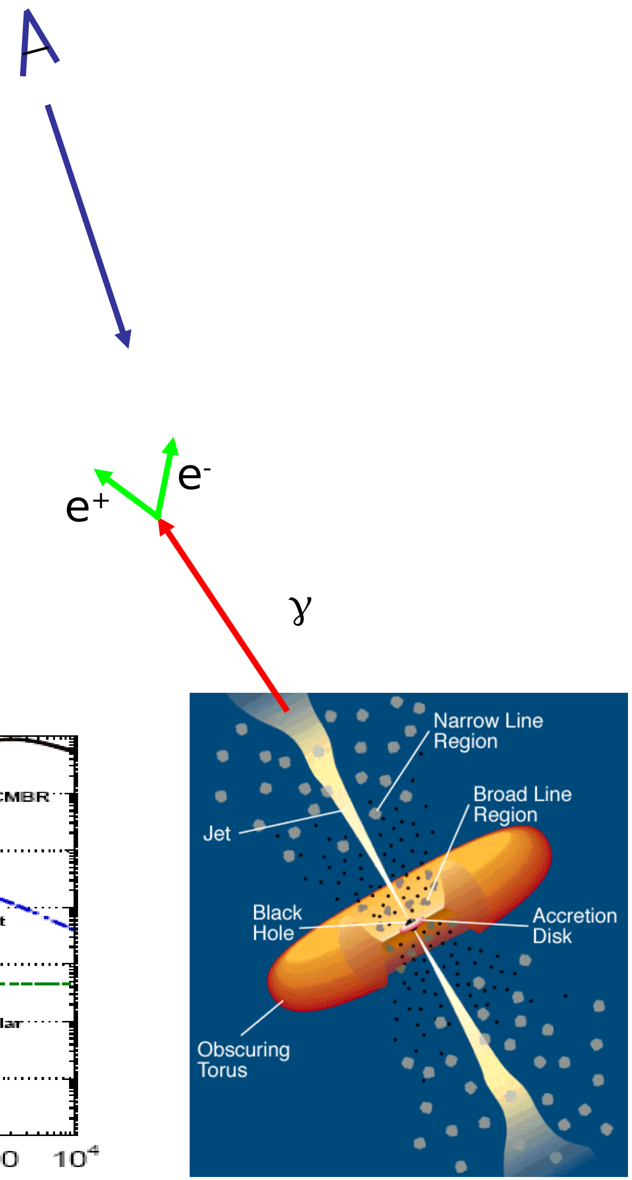
# γγ absorption by Extragalactic Background Light (EBL)



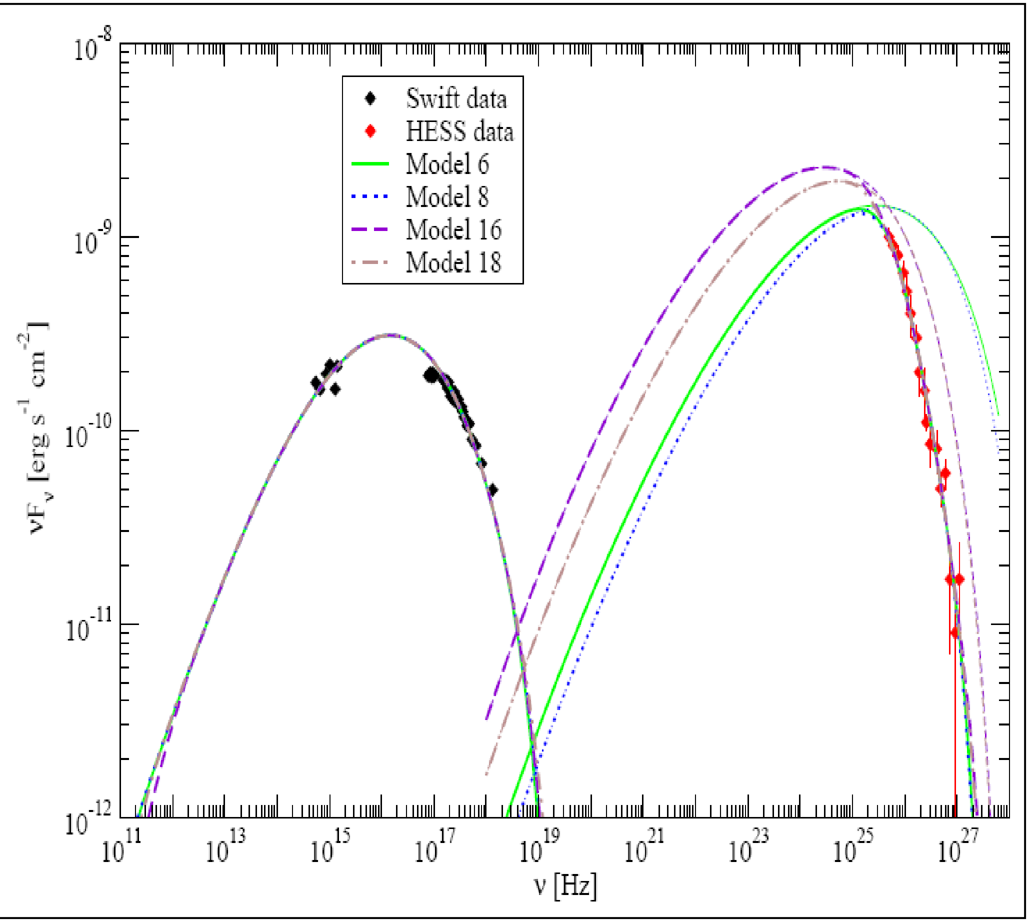

Stecker et al. (2006, 2007)



# Results




| Model | $\delta_D$ | B [mG] | $t_{var}$ [s] | $L_j$ [$10^{47}$ erg s$^{-1}$] |
|---|---|---|---|---|
| 6 | 895 | 2.5 | 30 | 4.5 |
| 8 | 390 | 3.0 | 300 | 2.7 |
| 16 | 261 | 81 | 30 | 0.5 |
| 18 | 139 | 57 | 300 | 0.4 |

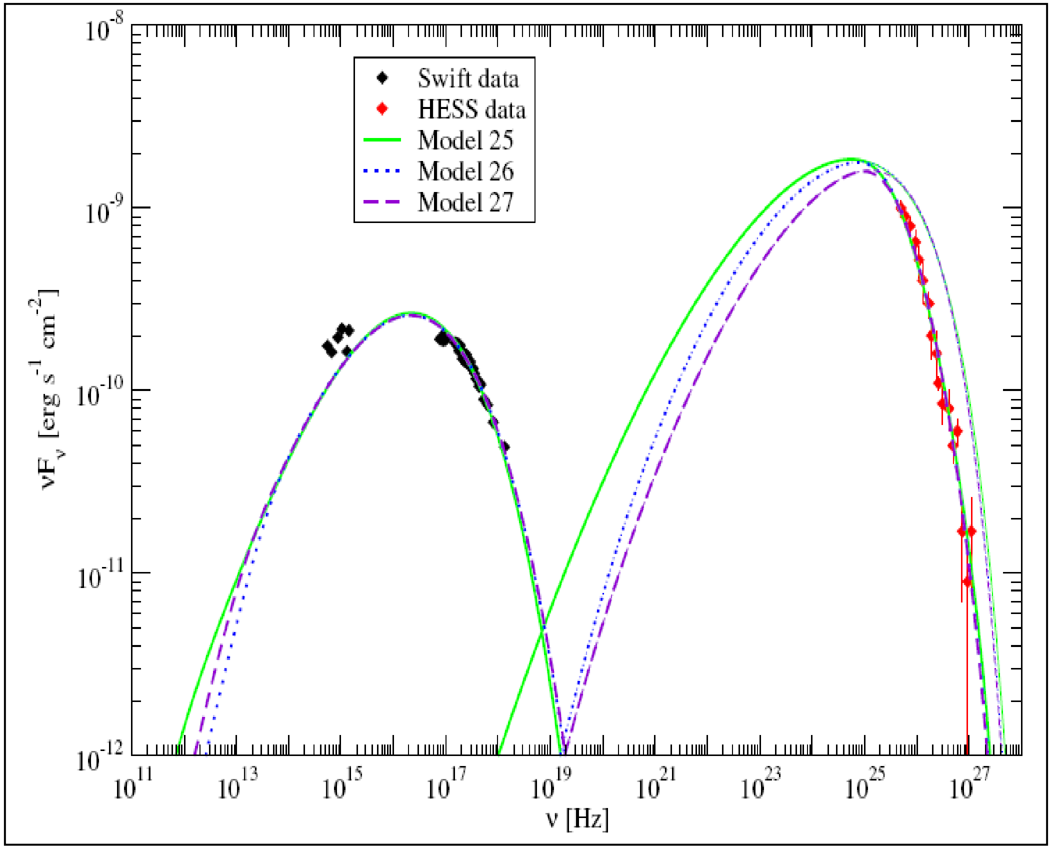
$\gamma'_{min} = 100$

Lower EBL

$\Gamma < 10$ on pc scales (Piner & Edwards 2004)

GLAST could distinguish between these models

# Results




| Model | $\delta_D$ | B [mG] | $t_{var}$ [s] | $L_j$ [$10^{46}$ erg s$^{-1}$] |
|---|---|---|---|---|
| 25 | 246 | 89 | 30 | 3.2 |
| 26 | 118 | 77 | 300 | 2.1 |
| 27 | 64 | 47 | 3000 | 2.2 |

Use electron spectrum to underfit optical data

Limited by $\gamma\gamma$ in blob

X/$\gamma$ correlations depends on $\gamma\gamma$ attenuation

# PKS 2155-304 Modeling

- Finke et al. (2008) model using Primack et al. (2005) EBL

$t_{var}$ = 2 days
$p_1$ = 3.2, 7.9e3 < $\gamma$ < 3.2e5
$p_2$ = 4.7, 3.2e5 < $\gamma$ < 7e6

B = 0.044 G
$\Gamma = \delta_D =$ 23.4

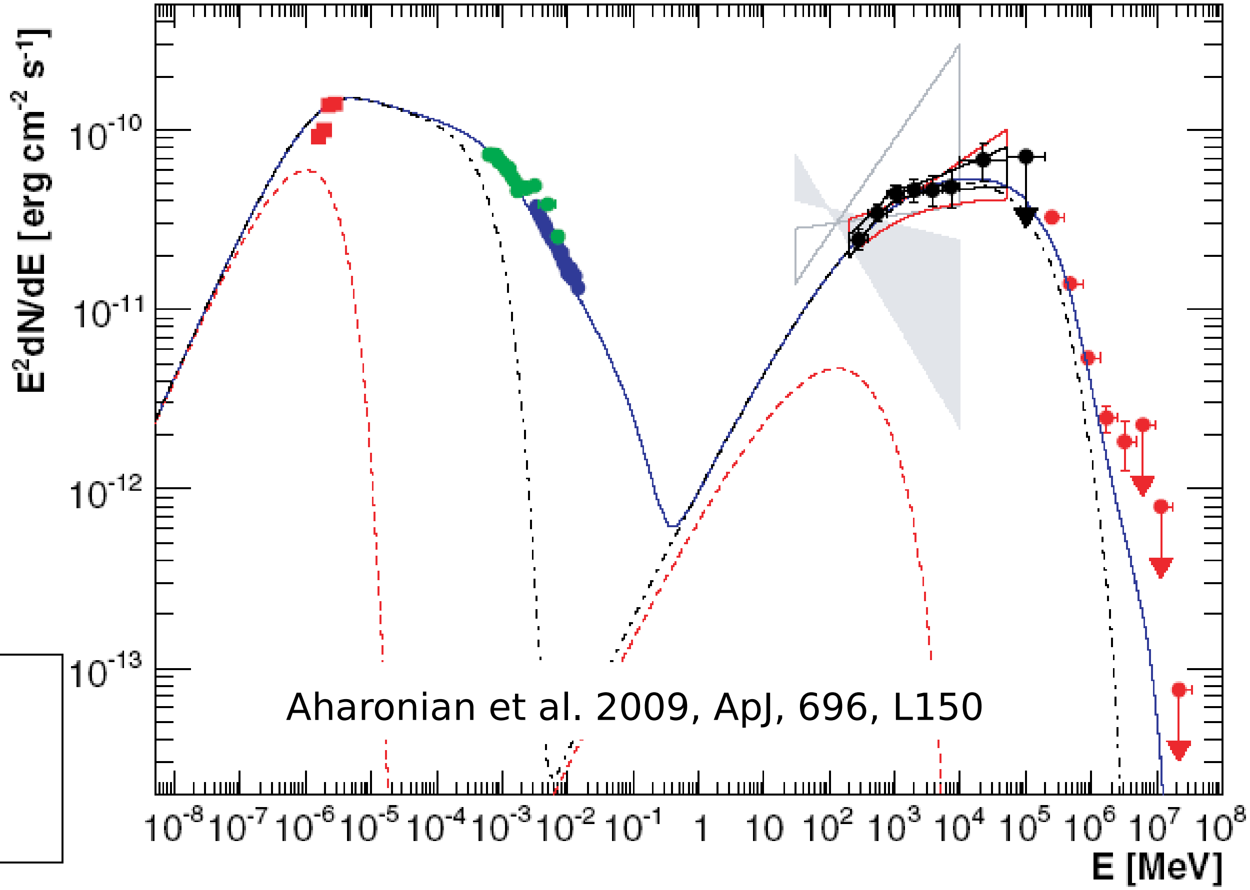
Jet power = 3.5e45 ergs/s
$L_B$ = 9.1e43 ergs/s
$L_{par}$ = 3.4e45 ergs/s

**Preliminary—not for distribution**

10 times more energy in nonthermal protons/hadrons as electrons

# Synchrotron/SSC Modeling of PKS 2155-304

- Fermi/HESS campaigns from 2008
- Fermi/RXTE campaigns from 2008/2009




**Preliminary—not for distribution**

# Monte Carlo Simulation of Synchrotron/SSC Model

Improved accuracy

Use accurate Compton kernel in the head-on approximation (Compton scattering, *not* inverse Compton scattering)

**Mersenne Twister for Random Number Generator**

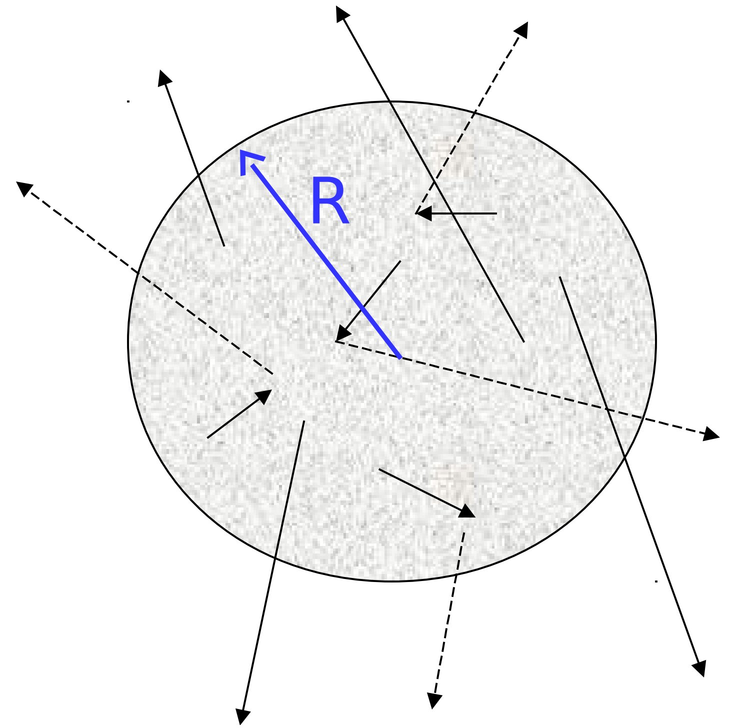
Check uniformity assumption
(cf. Gould 1979)

Can consider non-radial electron distributions

Realistic $\gamma\gamma$ opacity calculations

High energy tail for EBL s

Photon conservation




$$\frac{d\sigma_{\rm C}}{d\epsilon_s} \cong \frac{\pi r_e^2}{\gamma\bar{\epsilon}}\,\Xi_{\rm C}\,H\left(\epsilon_s; \frac{\bar{\epsilon}}{2\gamma}, \frac{2\gamma\bar{\epsilon}}{1+2\bar{\epsilon}}\right)$$

$$\Xi_{\rm C} \equiv y + y^{-1} - \frac{2\epsilon_s}{\gamma\bar{\epsilon}y} + \left(\frac{\epsilon_s}{\gamma\bar{\epsilon}y}\right)^2 \qquad y \equiv 1 - \frac{\epsilon_s}{\gamma}$$

$$\bar{\epsilon} = \gamma\epsilon(1 - \cos\hat{\psi})$$

# Synchrotron with Photon Conservation

Standard parameters:

$$n_e(\gamma) = k_{eo}\gamma^{-p} H(\gamma; \gamma_1, \gamma_2)$$

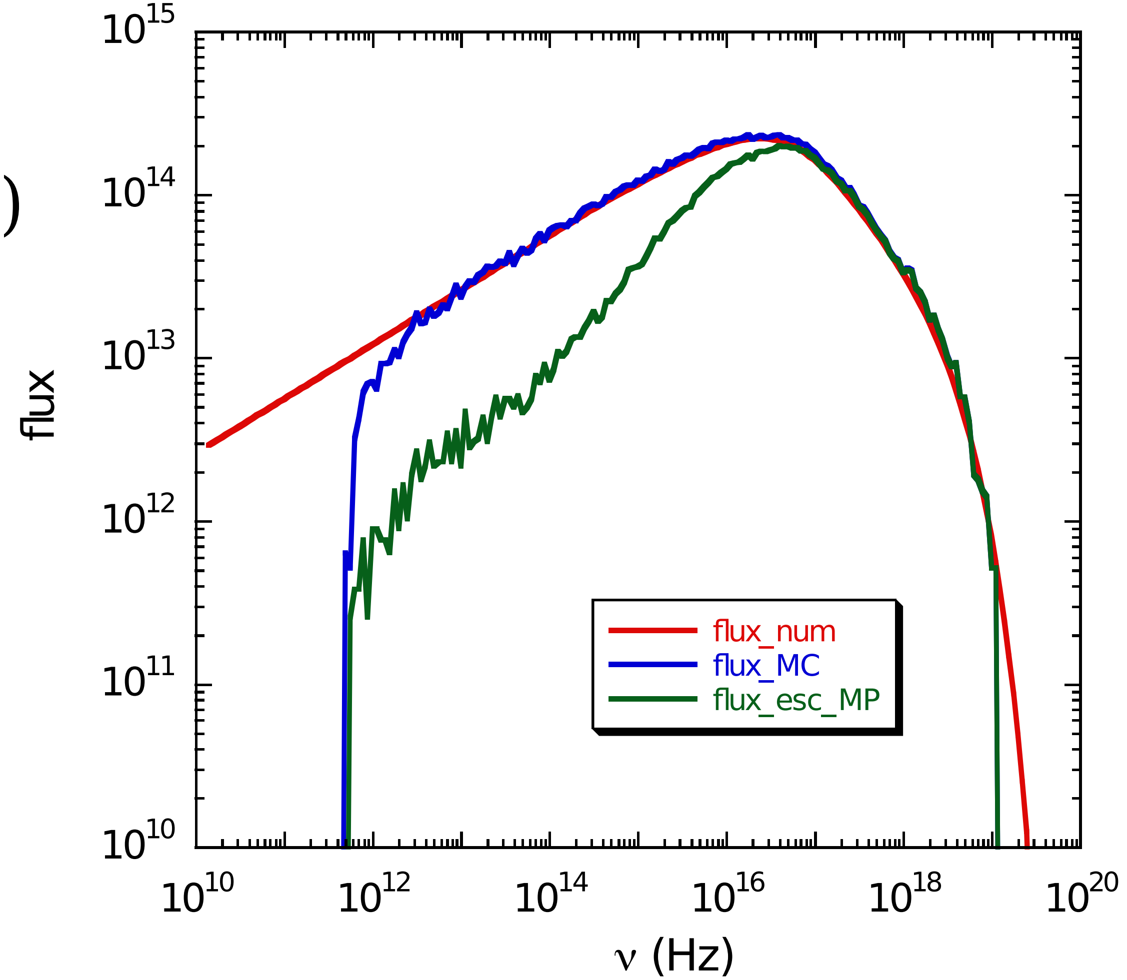
$$R = 10^{15}\ cm,\ p = 2.2$$

$$B = 1G$$

$$k_{eo} = \frac{n_{eo}(p-1)}{\gamma_1^{1-p} - \gamma_2^{1-p}}$$

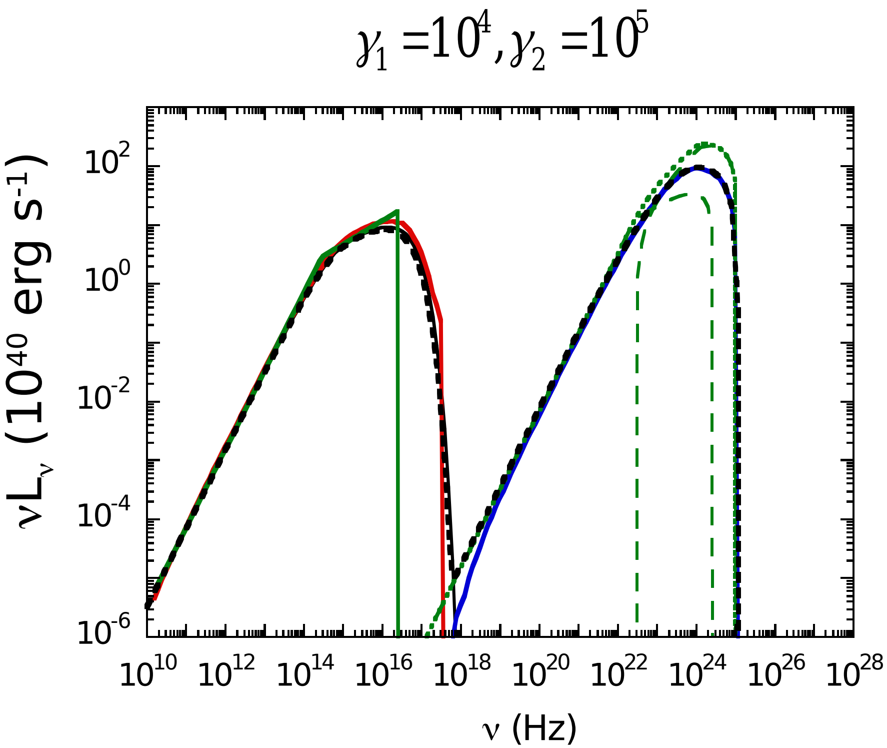
$$n_{eo} = 10^{10} cm^{-3},$$

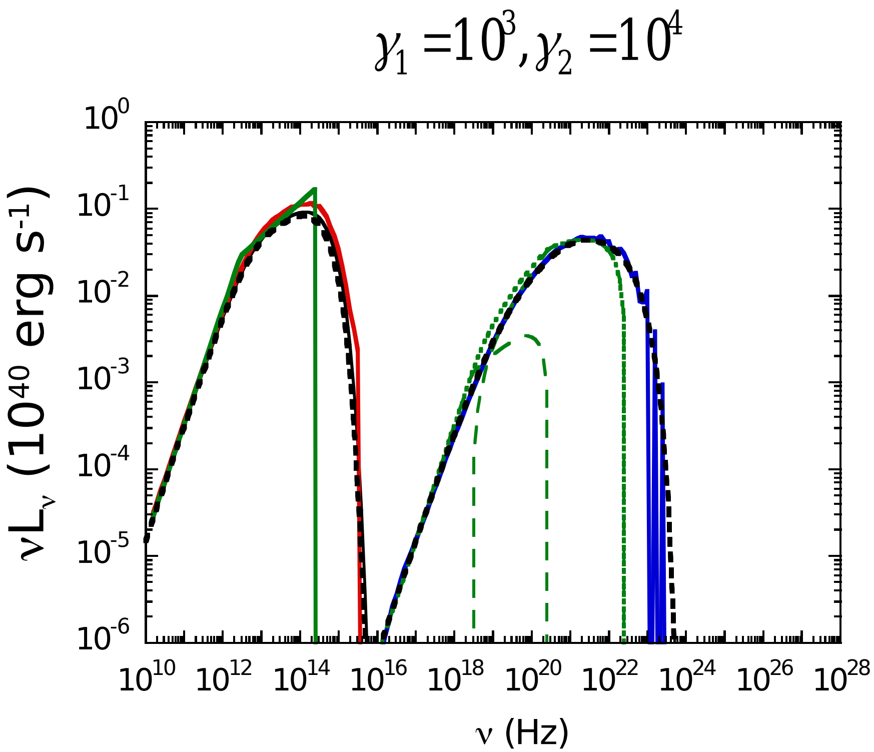
$$\gamma_1 = 10^5, \gamma_2 = 10^6$$




Scattering in KN regime
Solves “line of death” problem in GRB physics?

# Monte Carlo Synchrotron/SSC with Uniform Electrons and B-field



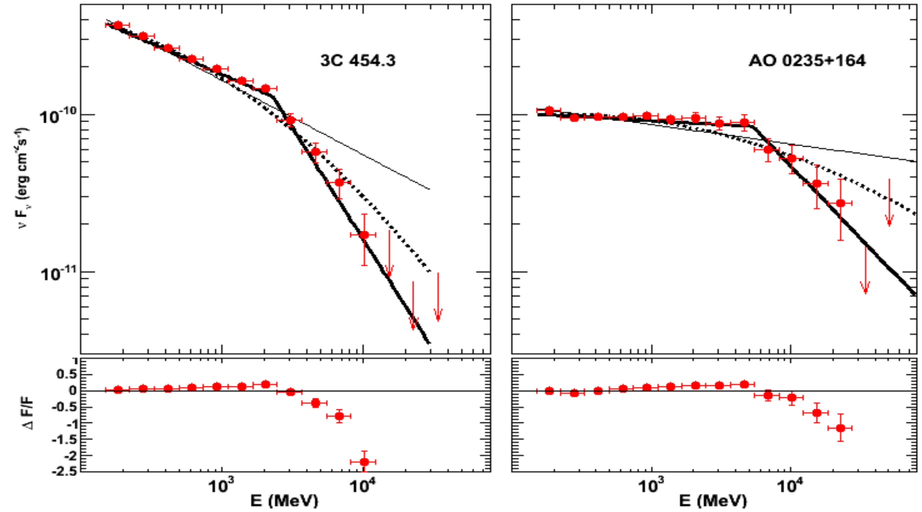



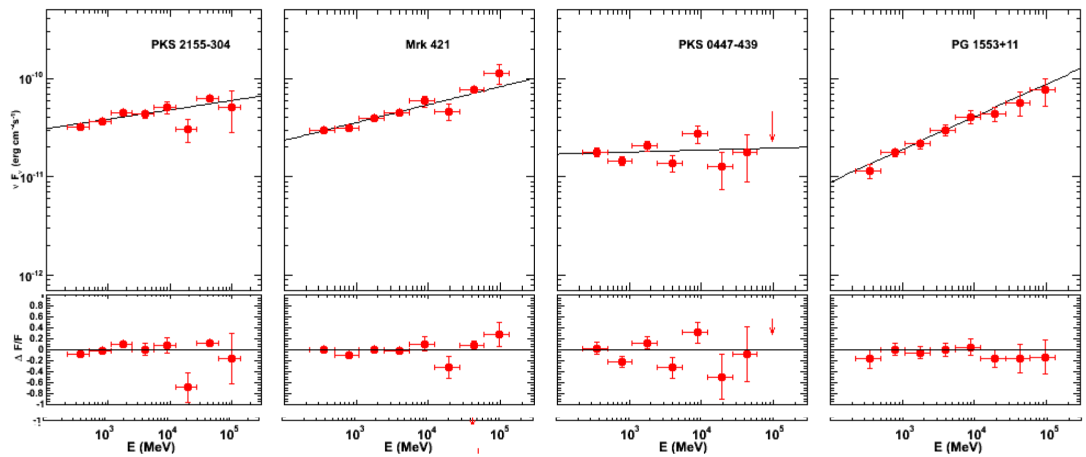

Comparison with δ-function approximation
Discrepancies in amplitude
Discrepancies in high-energy cutoff (could improve it by using exponentia
 cutoff in electron distribution)
Excellent agreement with numerical calculation (mean escape length = 3

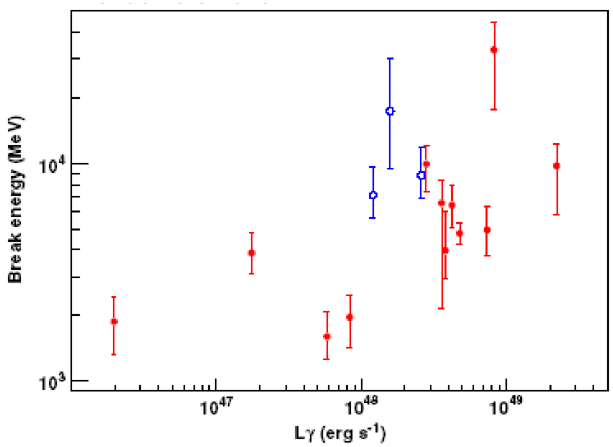
# Non-power law spectra

Abdo et al., 2010, ApJ, 710, 1271

- First definitive evidence of a spectral break above 100 MeV
- General feature in FSRQs and many BLLac-LSPs
- Absent in BLLac-HSPs
- Broken power law model seems to be favored
- $\Delta\Gamma \sim 1.0 > 0.5 \rightarrow$ not from radiative cooling
- Favored explanation: feature in the underlying particle distribution
- Implications for EBL studies and blazar contribution to extragalactic diffuse




Challenge for modelers to account for the break and the relative constancy of spectral index with tim

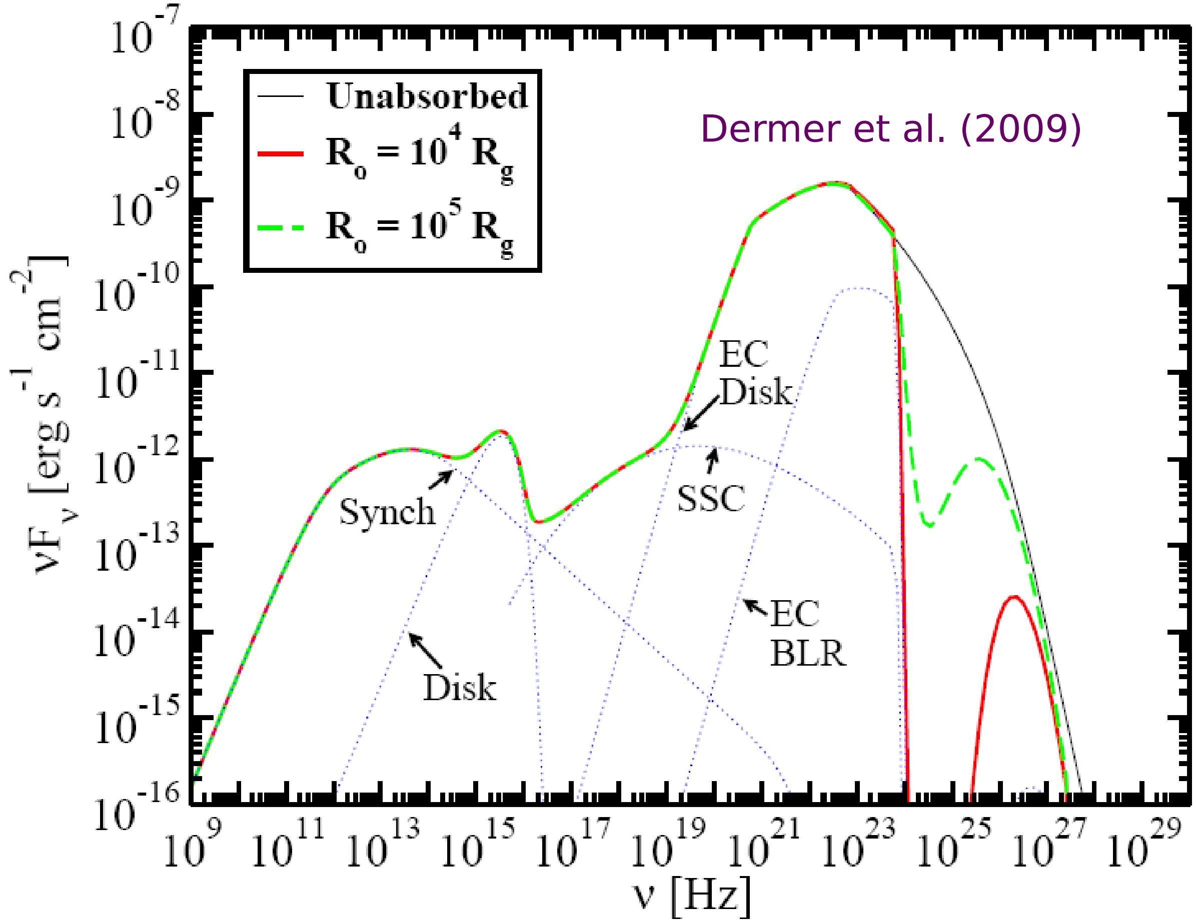
# FSRQ Modeling

At least three additional spectral components:
- Accretion disk
- EC Disk
- EC BLR

Lots of parameters

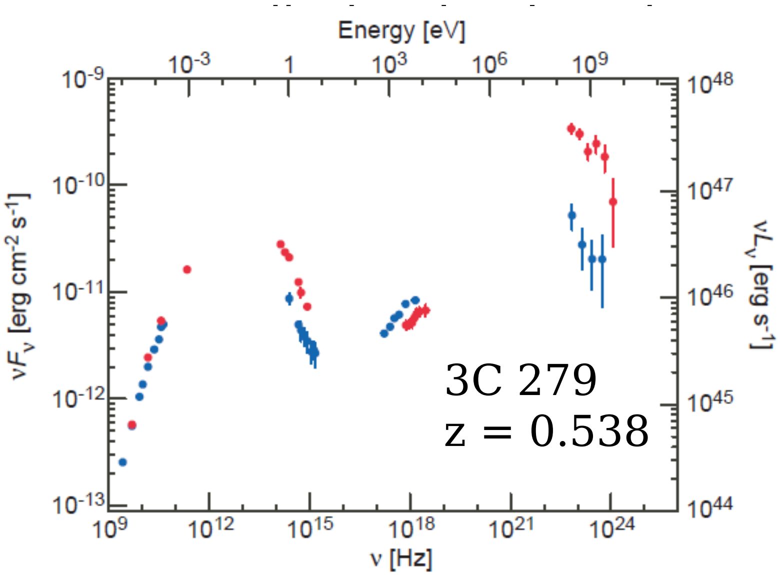
External radiation field provides a new source of opacity; need to perform Compton scattering and γγ opacity self-consistently

Opacity spectral break at a few GeV

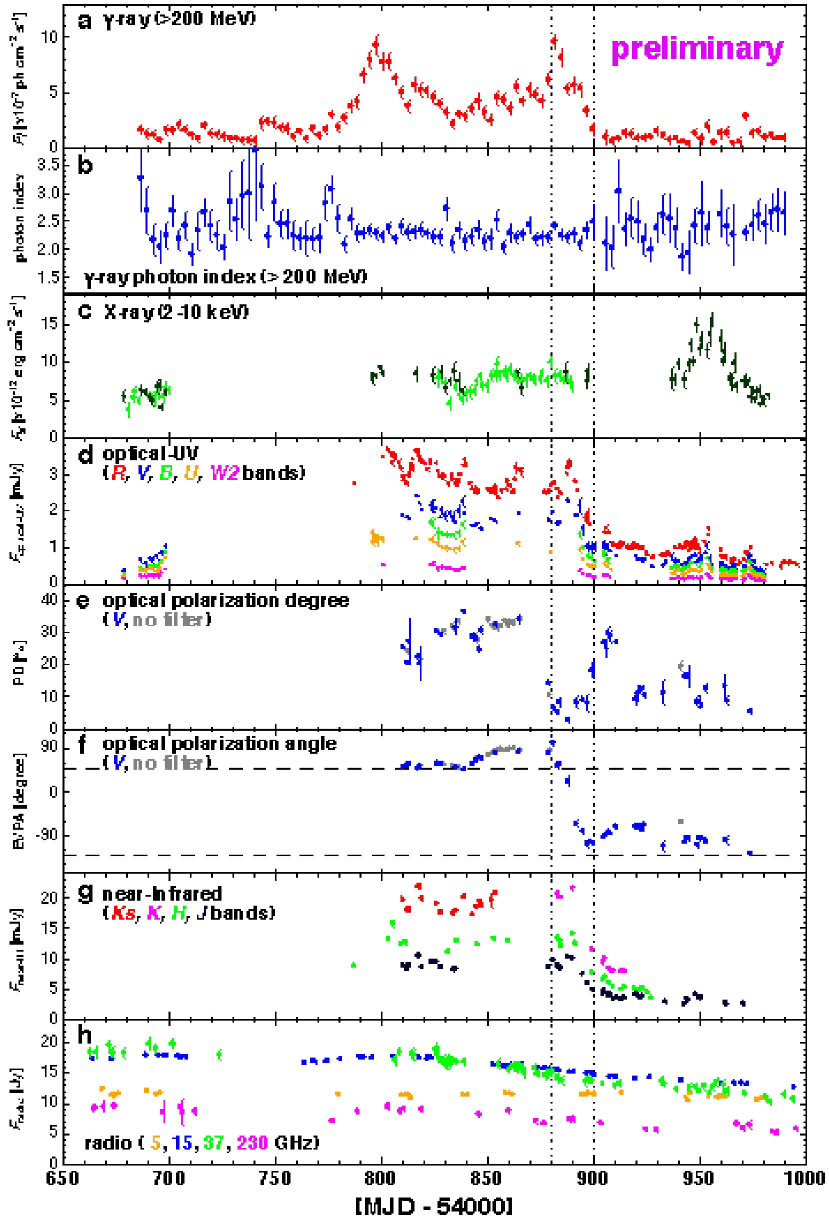


# 3C 279

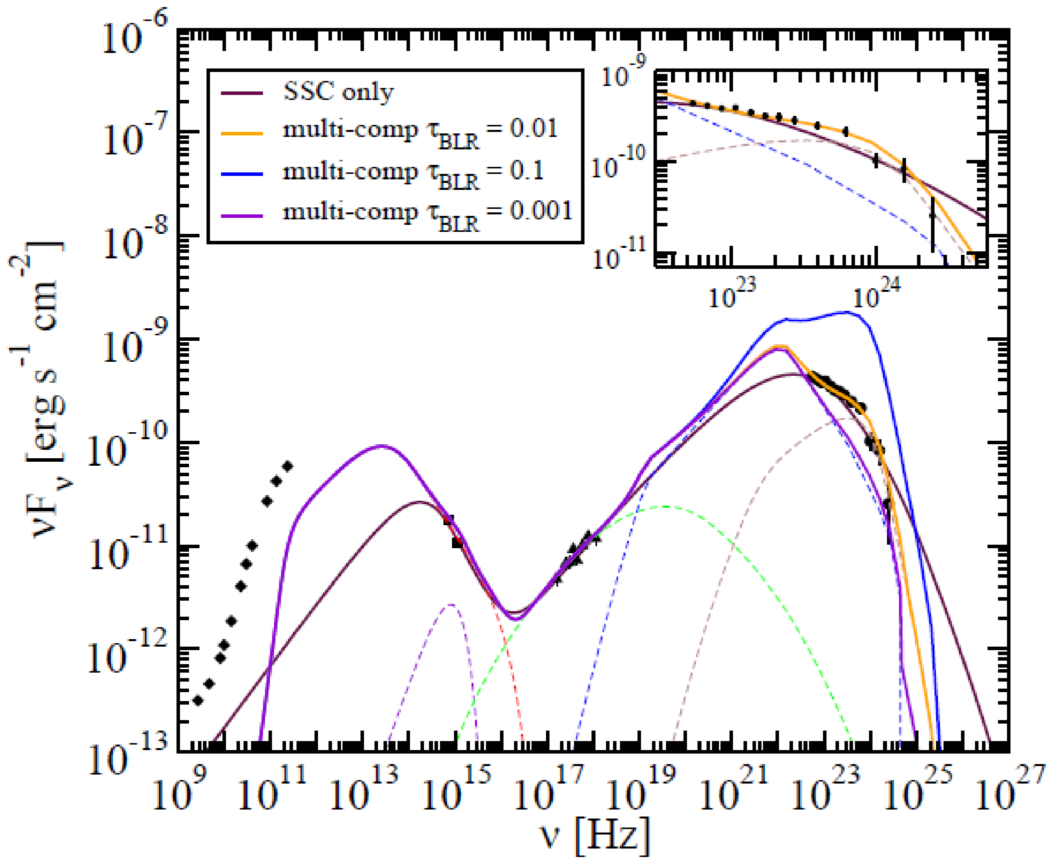
- Where are the γ-rays made?
- Monitor long-term behavior of light curve
- Correlates with changes in optical polarization and flux
- Highly ordered magnetic field over long timescale



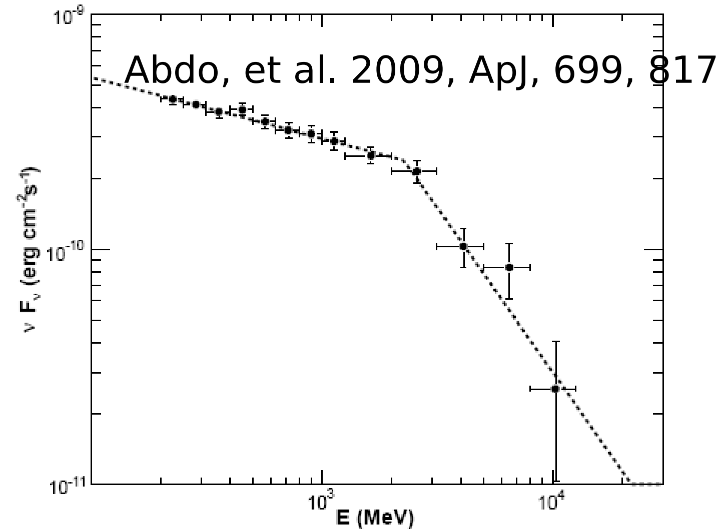

Abdo., et al. 2010, Nature, 463, 919



# Origin of Spectral Break in 3C454.3

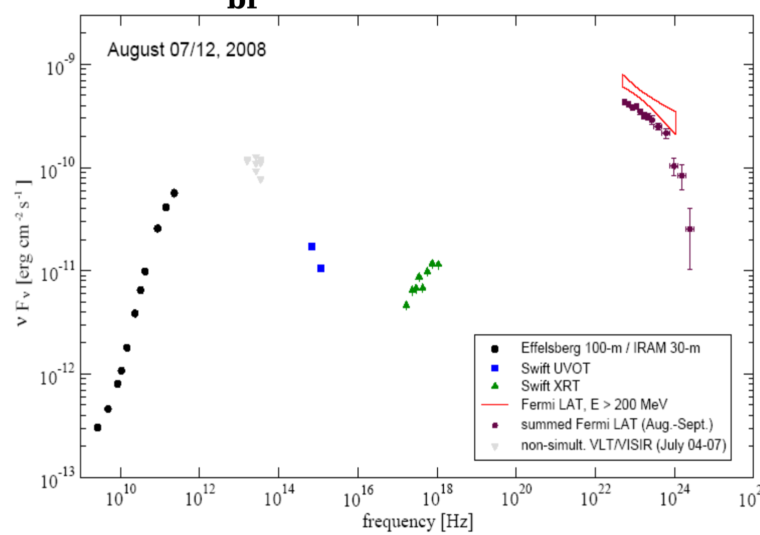



Finke and Dermer, 2010, submitted




Abdo, et al. 2009, ApJ, 699, 817

$\Gamma_{low}$ = **2.27** ± [illegible], $\Gamma_{high}$ = [illegible] ± [illegible] $E_{br}$ = [illegible] ± [illegible] **GeV**



# Relativistic jet physics

**New results on blazars and radio galaxies:**

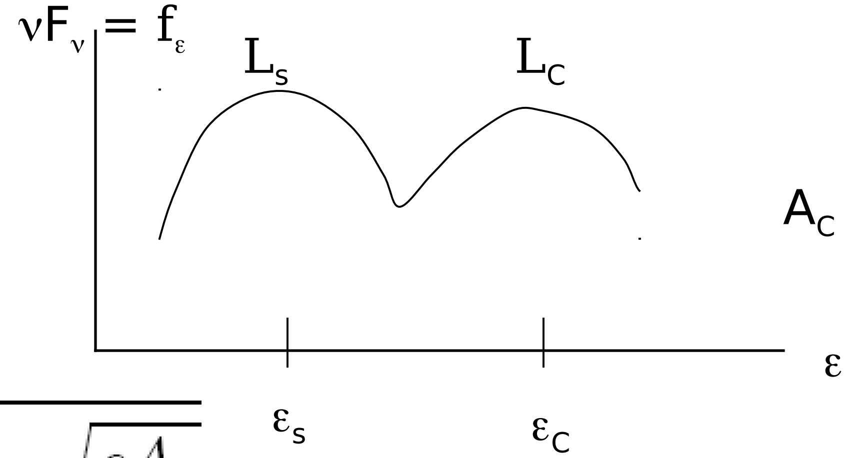
1. LBAS / 1LAC catalogs
2. Multi-GeV spectral softening in FSRQs, LBLs, IBLs; not XBLs
3. Multiwavelength  quasi-simultaneous SEDs including GeV emission for radio galaxies, BL Lacs and FSRQs
4. 3C 279, PKS 1510-089: location of emission site; complexity of magnetic field
5. Use SED to constrain redshift from EBL model
6. Long (mo – yr) timescale light curves
7. High energy photons from blazar sources: minimum Doppler factor
8. Contemporaneous data sets for, e.g.,
    1. FSRQs 3C 454.3, 3C 279
    2. BL Lacs: Mrk 421, PKS 2155-304
    3. Radio galaxies: Cen A, M87, 3C 84

# Back-up Slides

# Synchrotron/SSC model in the Thomson regime

Can measure 6 defining quantities for syn/SSC model:

z, $t_v$




$A_C = L_C/L_s$

$$\Gamma \cong \frac{1}{\epsilon_s} \sqrt{\frac{\epsilon_C}{ct_v B_{cr}}\sqrt{\frac{2L_s}{cA_c}}}$$

$$B \cong \frac{(1+z)B_{cr}\epsilon_s^3}{\epsilon_C^{3/2}} \sqrt{ct_v B_{cr}\sqrt{\frac{cA_c}{2L_s}}}$$

(Ghisellini et al. 1996)

$\Gamma > \Gamma_{min}$

$$B_{cr} = m_e^2 c^3/e\hbar \cong 4.414 \times 10^{13}\ \mathrm{G}$$

Thomson regime $\epsilon_C \epsilon_s \lesssim \left(\frac{\Gamma}{1+z}\right)^2$

# Nonthermal Electron Synchrotron Radiation

If electrons are assumed to radiate the observed synchrotron $\nu F_\nu$ spectrum, then in the $\delta$-function approximation for synchrotron emissivity

$$f_\varepsilon^{syn} = \frac{\delta_D^4 \varepsilon' L'(\varepsilon')}{4\pi d_L^2}, \; \varepsilon' L'(\varepsilon') \cong \frac{4}{3} c\sigma_T \frac{B'^2}{8\pi} \gamma'^2 \times \gamma' N_e'(\gamma')$$

So
$$f_\varepsilon^{syn} = \frac{\delta_D^4 \varepsilon' L'(\varepsilon')}{4\pi d_L^2} \;\Rightarrow\; N_e'(\gamma') \cong \frac{24\pi^2 d_L^2 f_\varepsilon^{syn}}{c\sigma_T B'^2 \delta_D^4 \gamma'^3}$$

$$\varepsilon' \cong \frac{B'}{B_{cr}} \gamma'^2, \quad \varepsilon \approx \frac{\delta_D \varepsilon'}{1+z} \Rightarrow \gamma' \cong \sqrt{\frac{(1+z)\varepsilon B_{cr}}{\delta_D B'}}$$